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(54) **ELECTRODE AND DECOMPOSABLE ELECTRODE MATERIAL FOR Z-PINCH PLASMA CONFINEMENT SYSTEM**

(71) Applicant: **ZAP ENERGY, INC.**, Seattle, WA (US)

(72) Inventors: **Benjamin Joseph LEVITT**, Seattle, WA (US); **Matthew Colin THOMPSON**, Mukilteo, WA (US)

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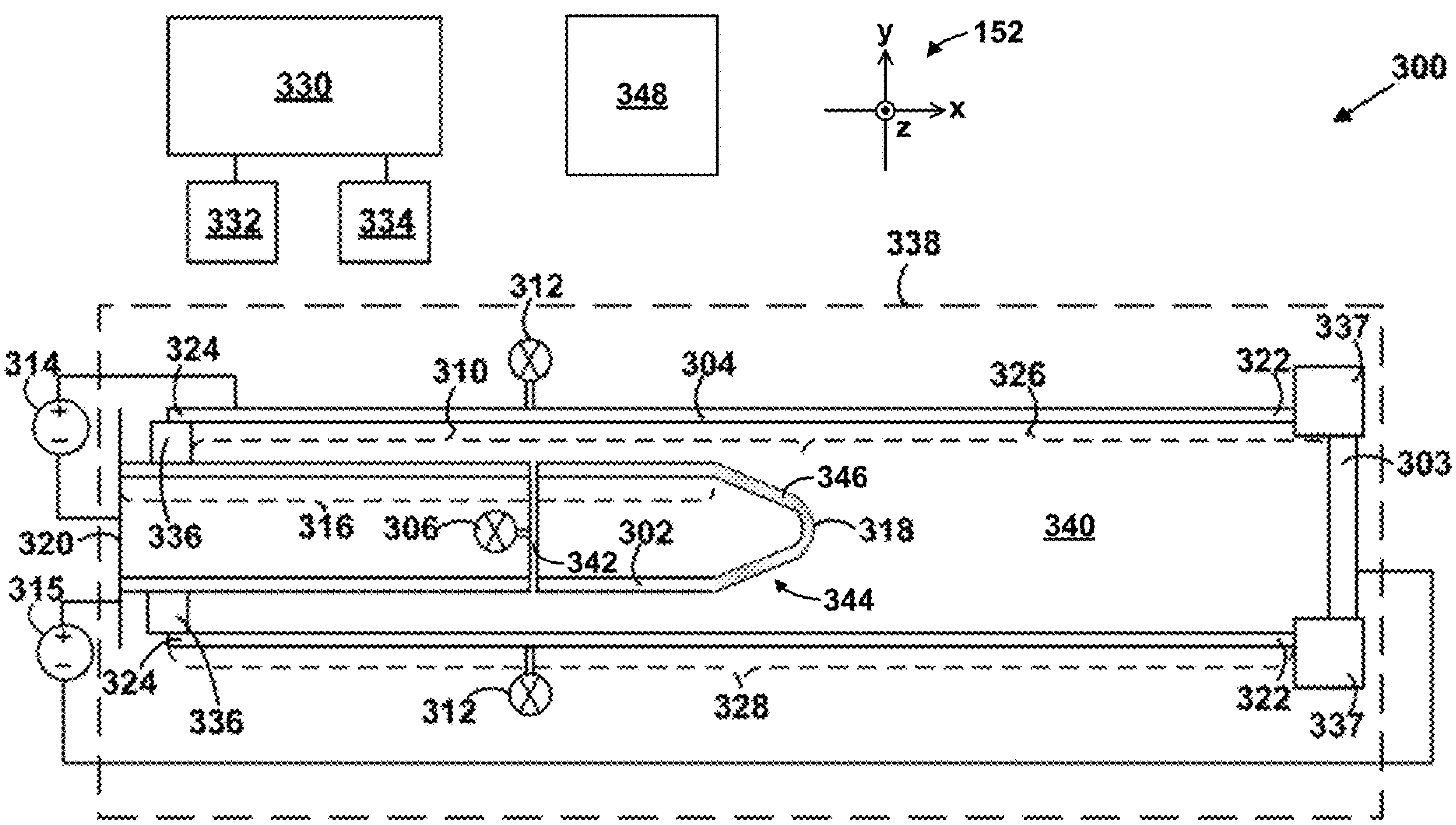
CPC *G21B 1/05* (2013.01)

(57) **ABSTRACT**

Methods and systems are provided for Z-pinch plasma and other plasma confinement utilizing various electrode compositions and configurations. In one example, a plasma confinement system includes a plurality of electrodes, each electrode of the plurality of electrodes arranged coaxially with respect to an assembly region of the plasma confinement system and positioned so as to be exposed to the assembly region, wherein one or more electrodes of the plurality of electrodes includes an electrode material which releases hydrogen gas above a threshold temperature. In an additional or alternative example, a plasma confinement system includes an electrode body including a nosecone, and a liquid metal, a portion of the liquid metal forming a protective film between a surface of the nosecone and an exterior of the nosecone during operation of the plasma confinement system.



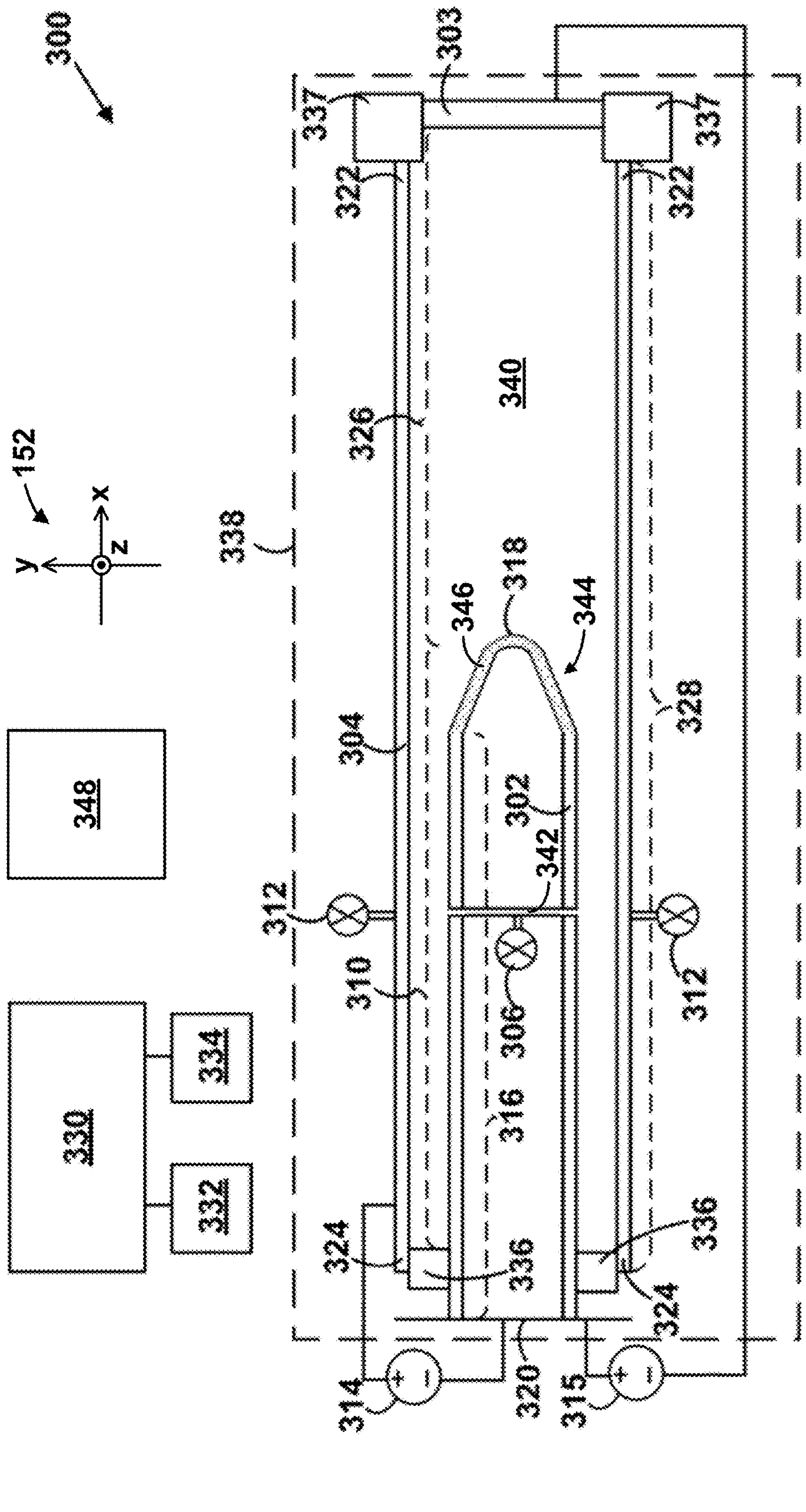

300
303
337
337
322
322
326
340
152
x
y
z
338
346
318
344
304
328
302
342
348
312
312
310
306
330
334
332
316
324
336
336
324
314
320
315

FIG. 1

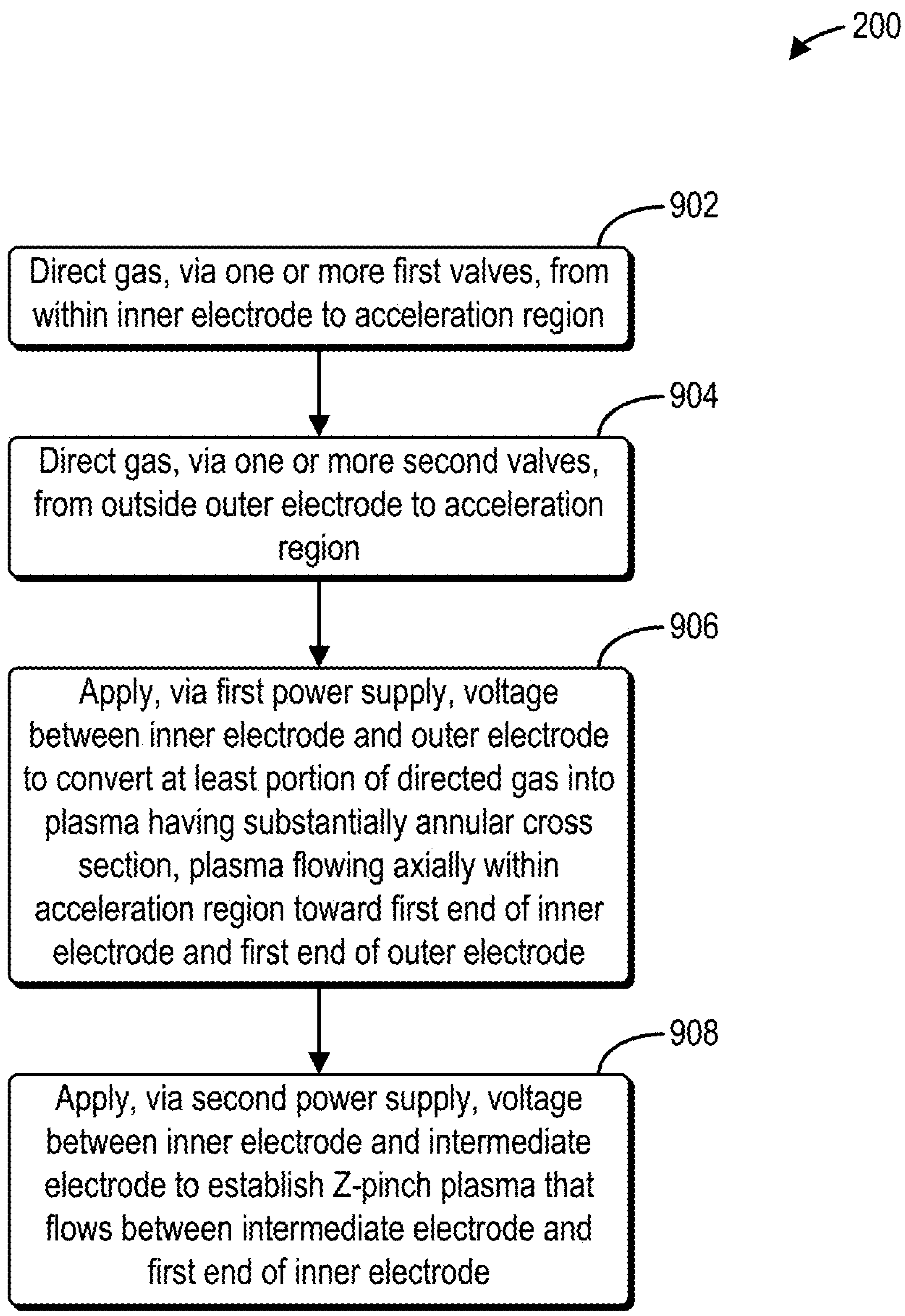

200
902
Direct gas, via one or more first valves, from within inner electrode to acceleration region
904
Direct gas, via one or more second valves, from outside outer electrode to acceleration region
906
Apply, via first power supply, voltage between inner electrode and outer electrode to convert at least portion of directed gas into plasma having substantially annular cross section, plasma flowing axially within acceleration region toward first end of inner electrode and first end of outer electrode
908
Apply, via second power supply, voltage between inner electrode and intermediate electrode to establish Z-pinch plasma that flows between intermediate electrode and first end of inner electrode

FIG. 2

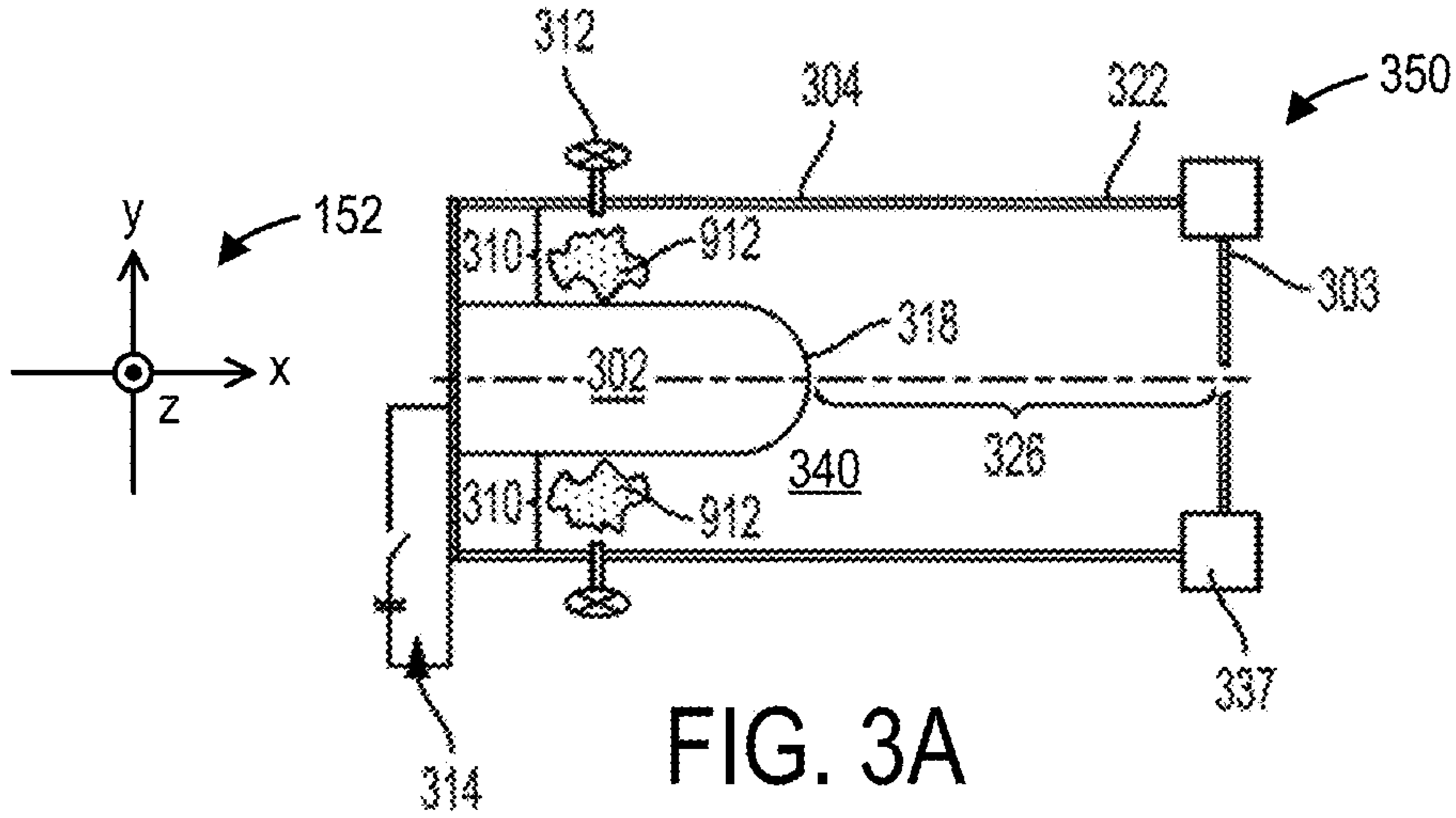


FIG. 3A

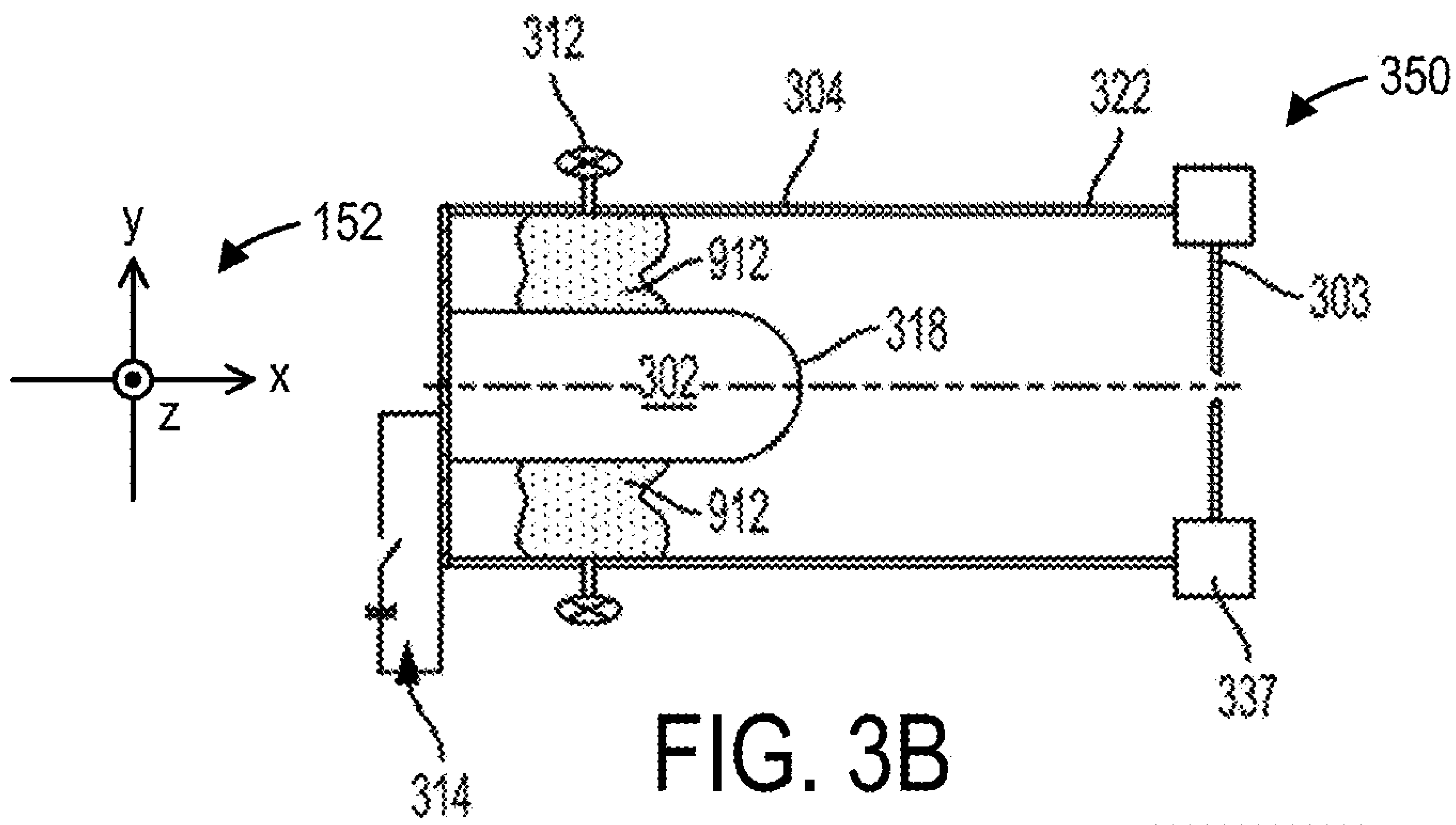


FIG. 3B

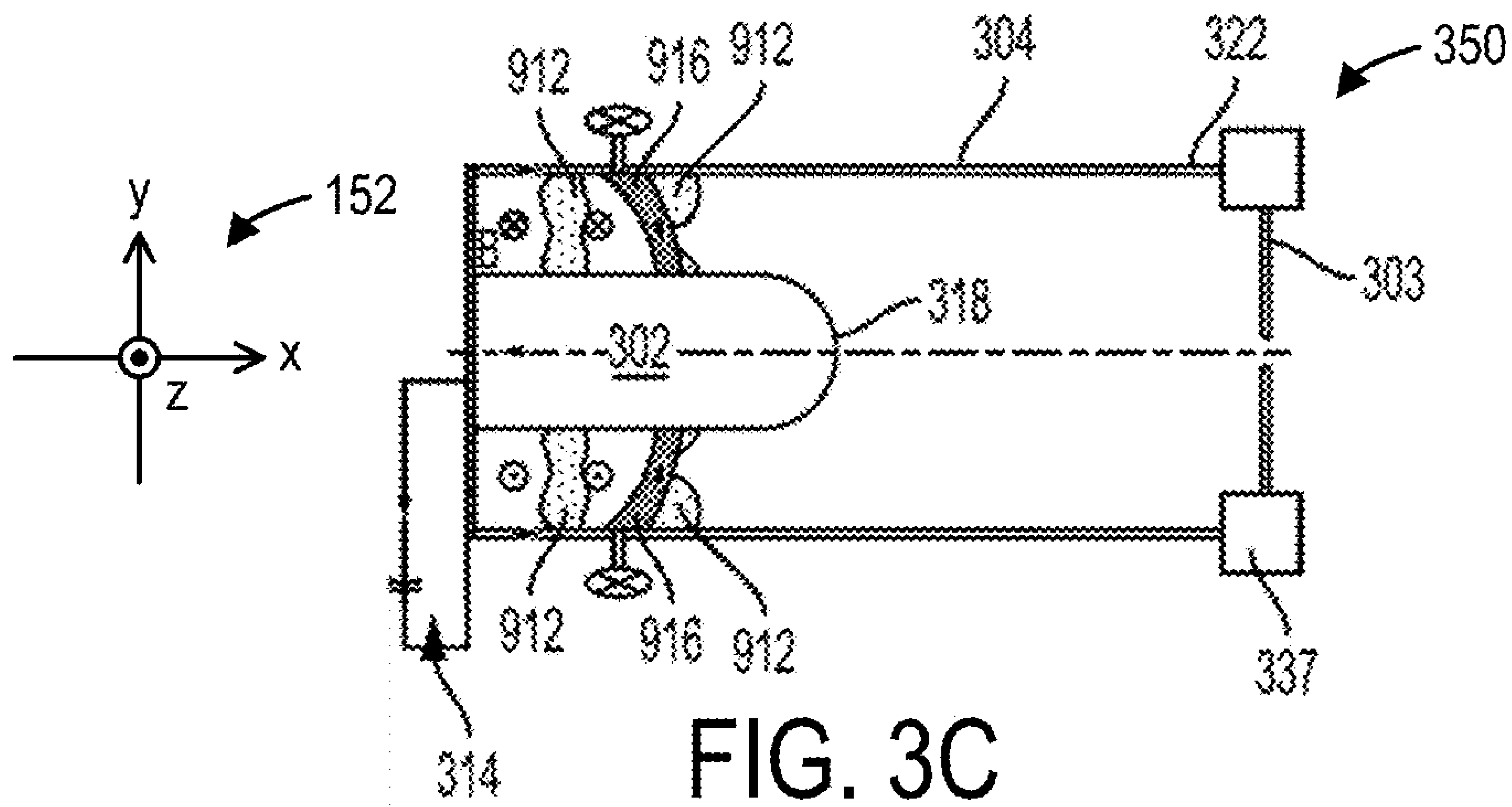


FIG. 3C

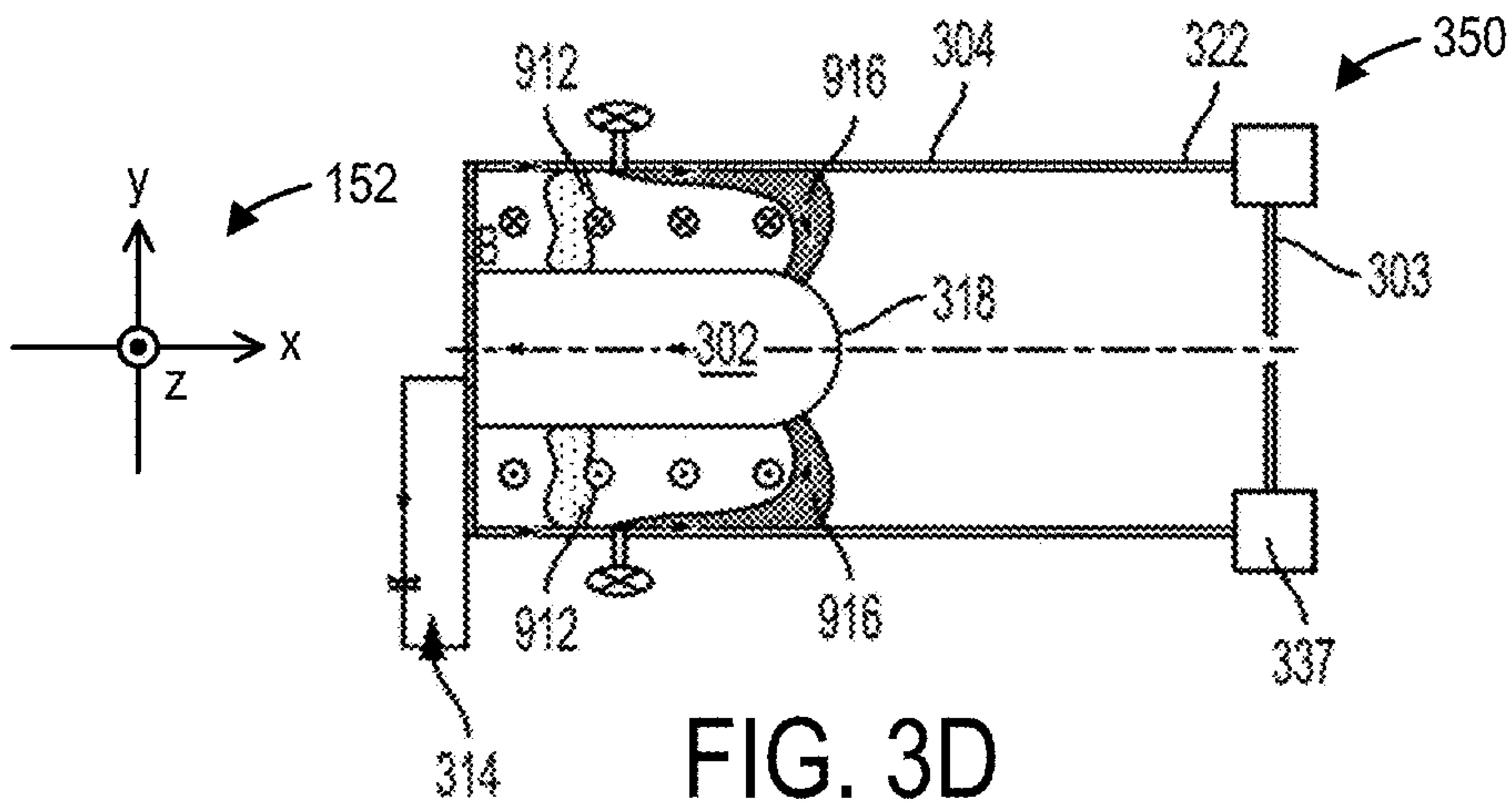


FIG. 3D

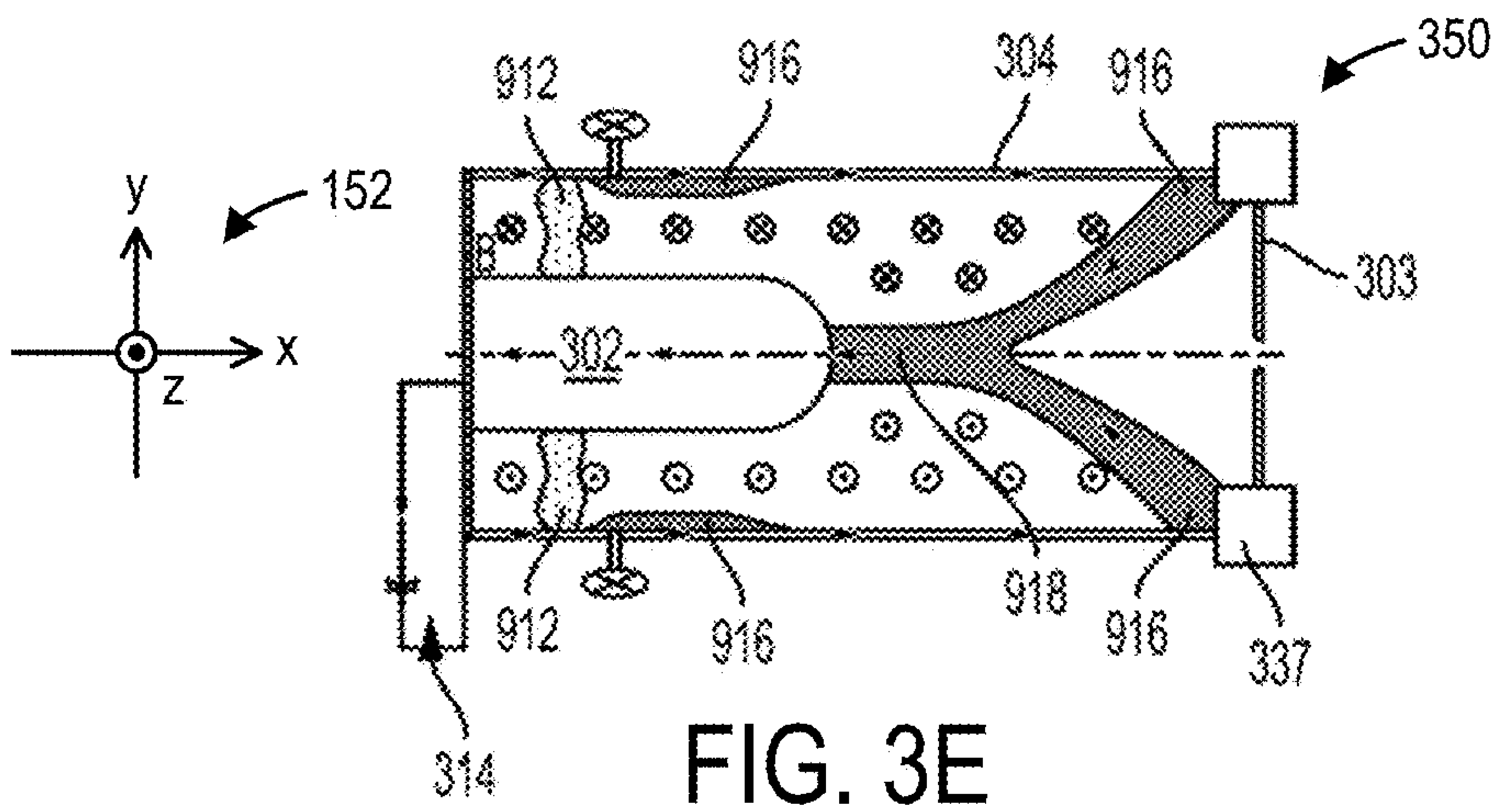


FIG. 3E

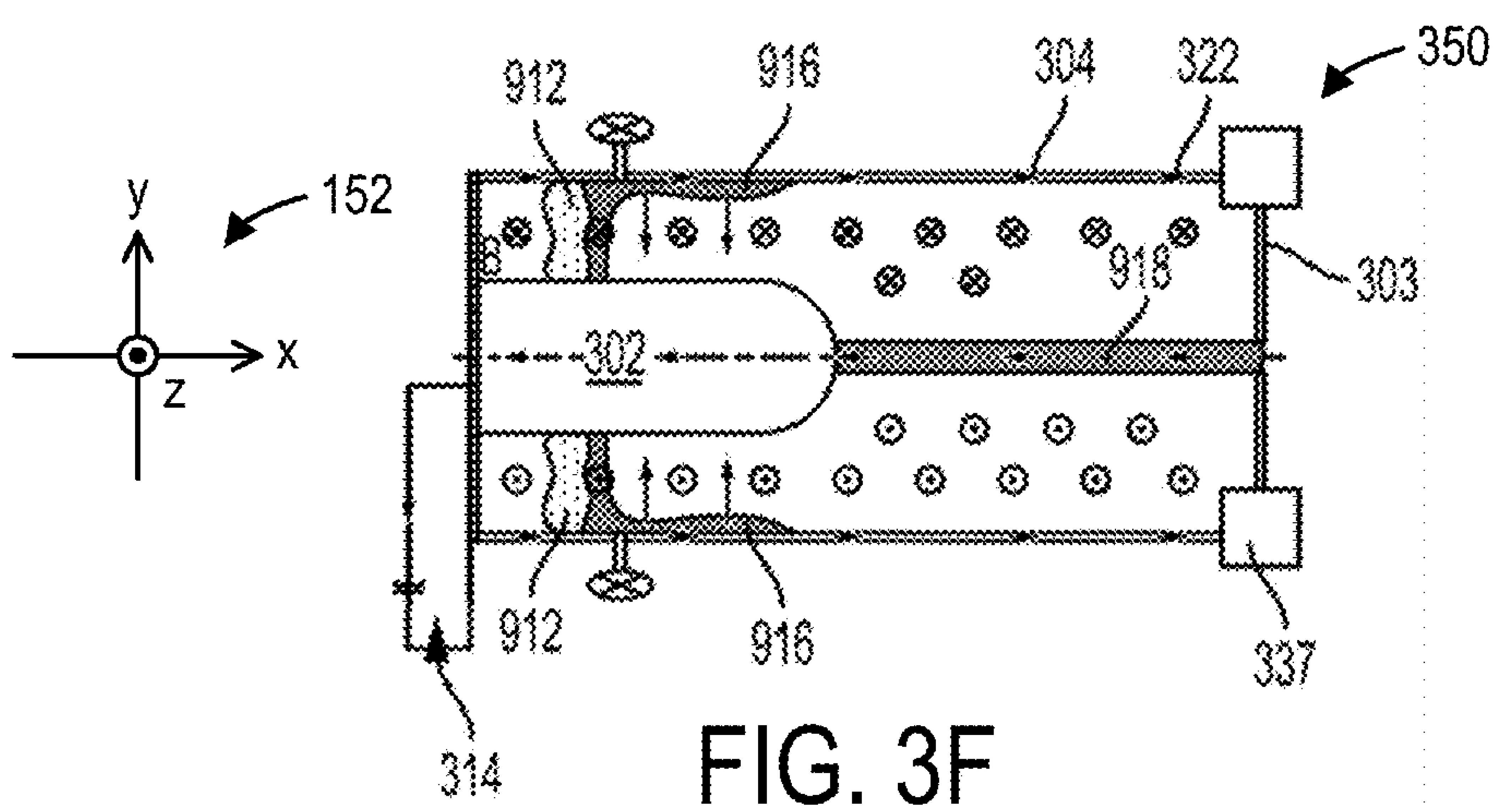


FIG. 3F

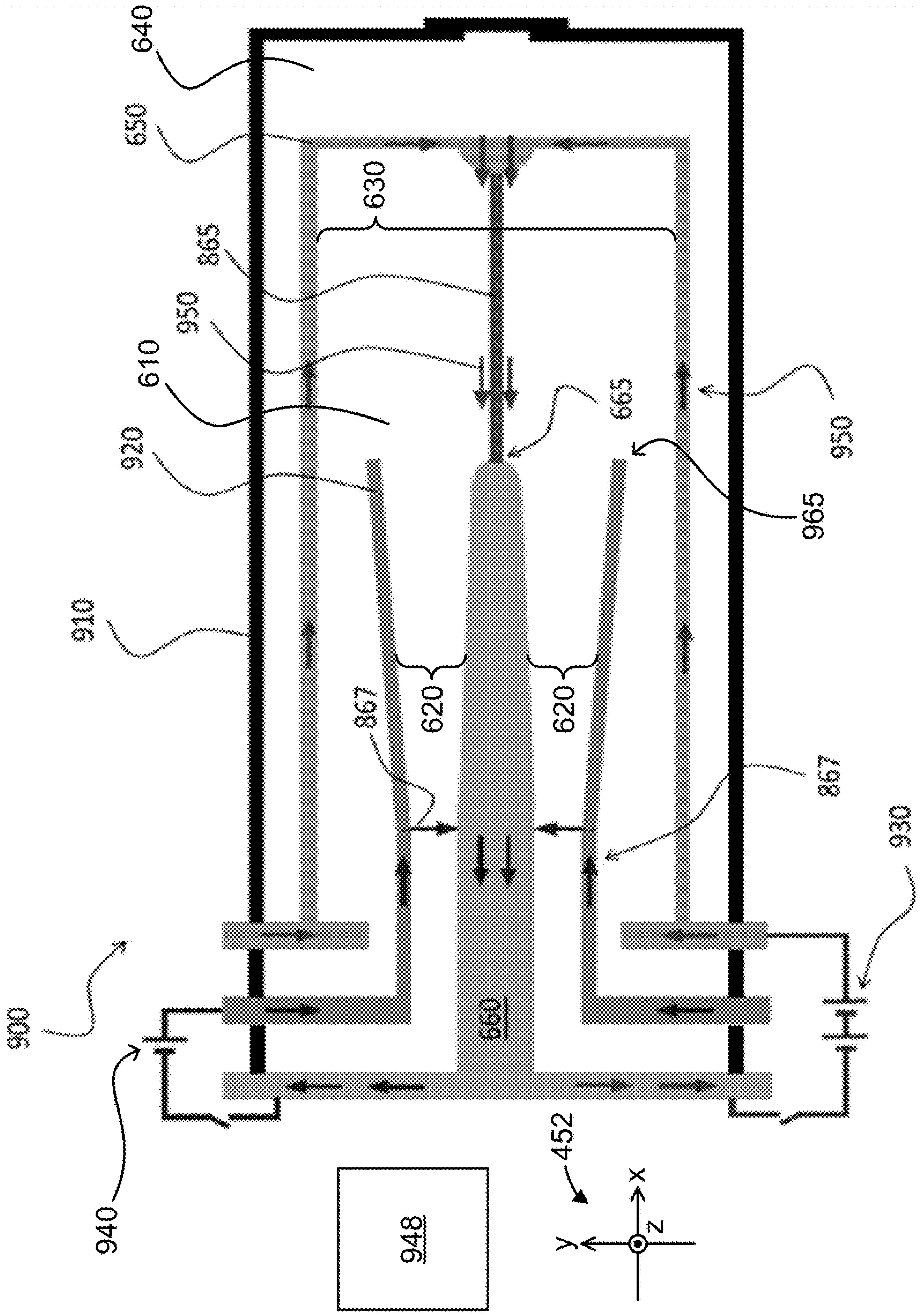

640
650
630
865
950
610
665
920
950
965
910
867
620
620
867
930
900
660
940
452
948
x
y
z

FIG. 4

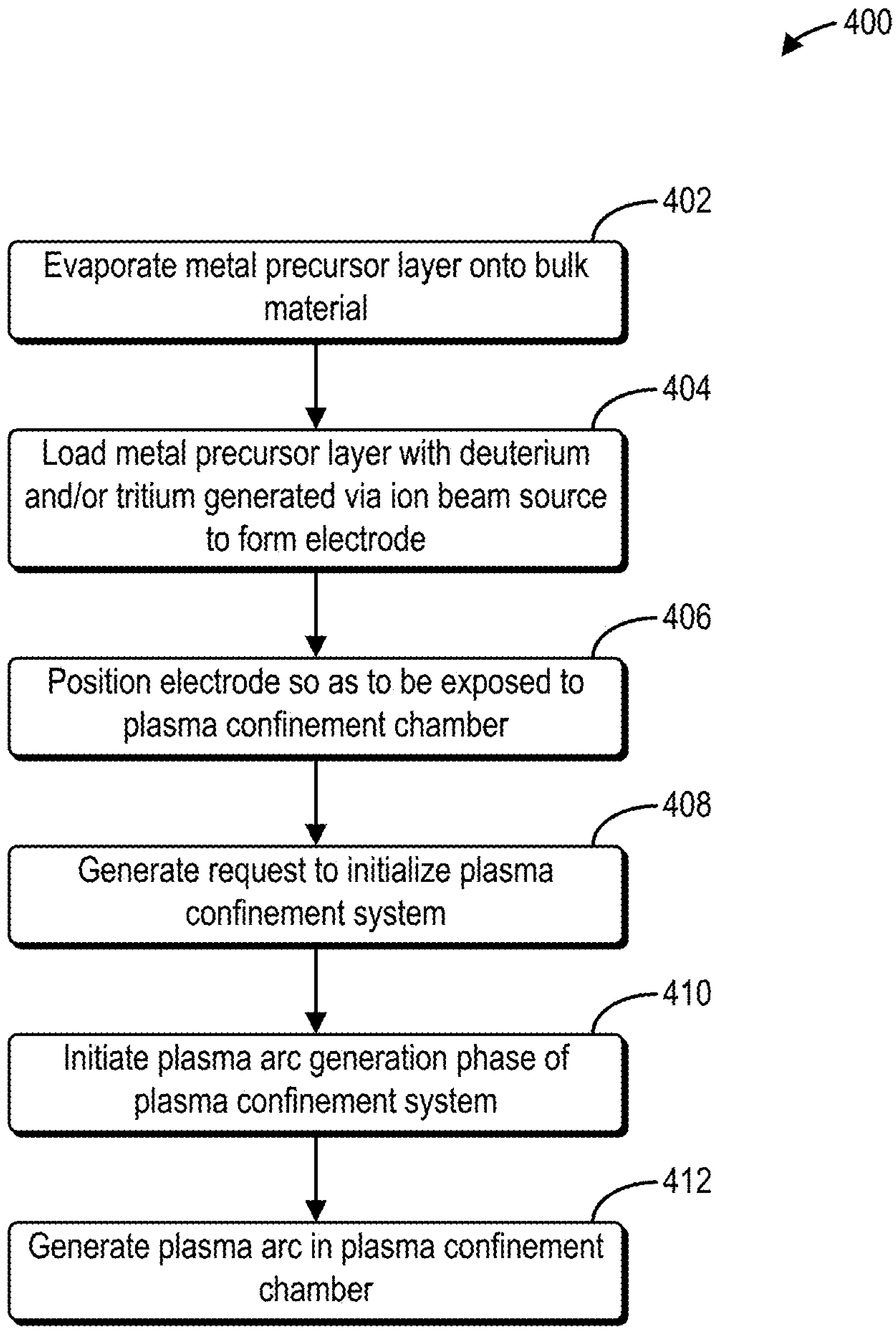

400
402
Evaporate metal precursor layer onto bulk material
404
Load metal precursor layer with deuterium and/or tritium generated via ion beam source to form electrode
406
Position electrode so as to be exposed to plasma confinement chamber
408
Generate request to initialize plasma confinement system
410
Initiate plasma arc generation phase of plasma confinement system
412
Generate plasma arc in plasma confinement chamber

FIG. 5

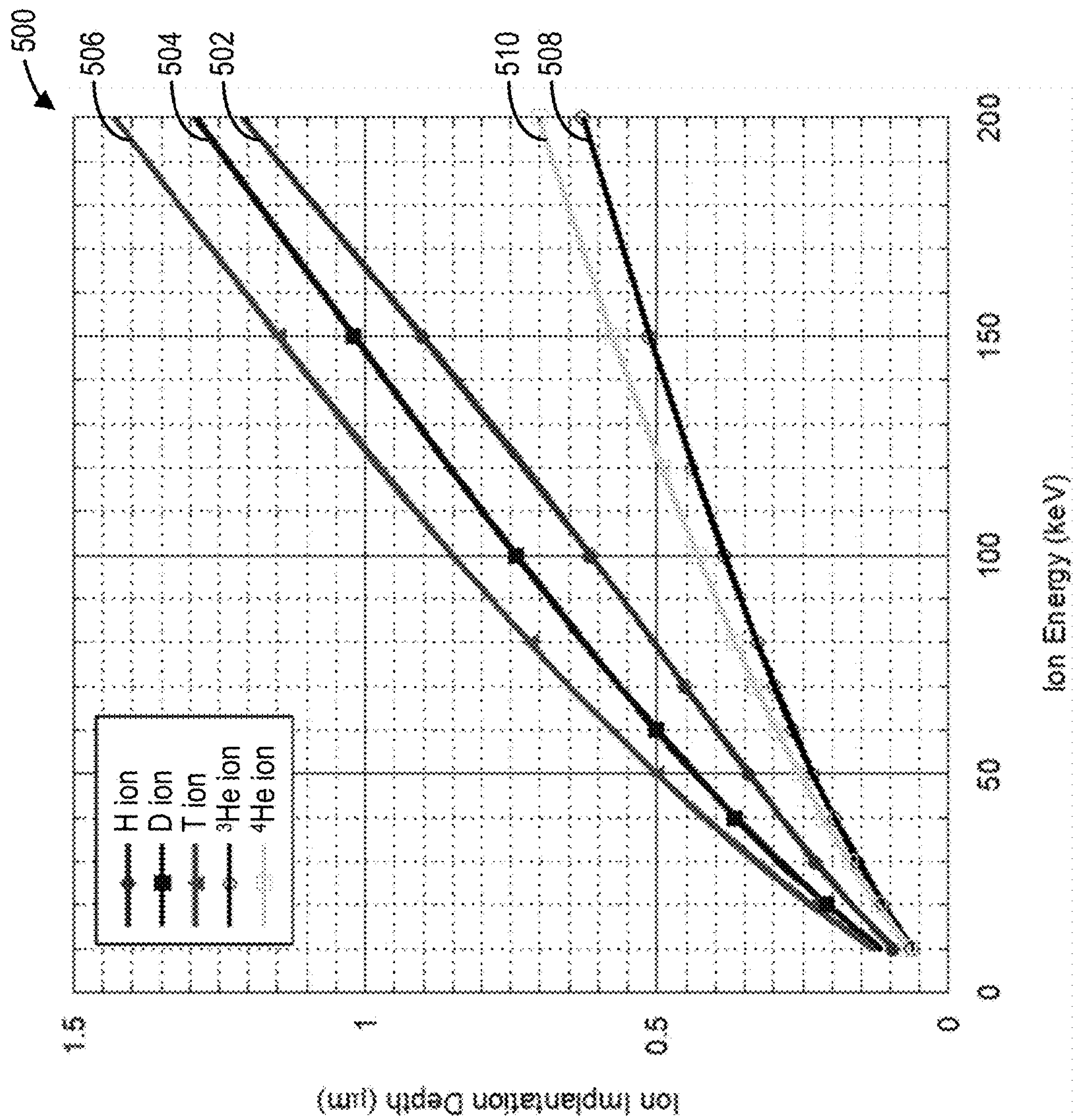

500
506
504
502
510
508
H ion
D ion
T ion
3He ion
4He ion
Ion Implantation Depth (μm)
1.5
1
0.5
0
Ion Energy (keV)
0
50
100
150
200

FIG. 6

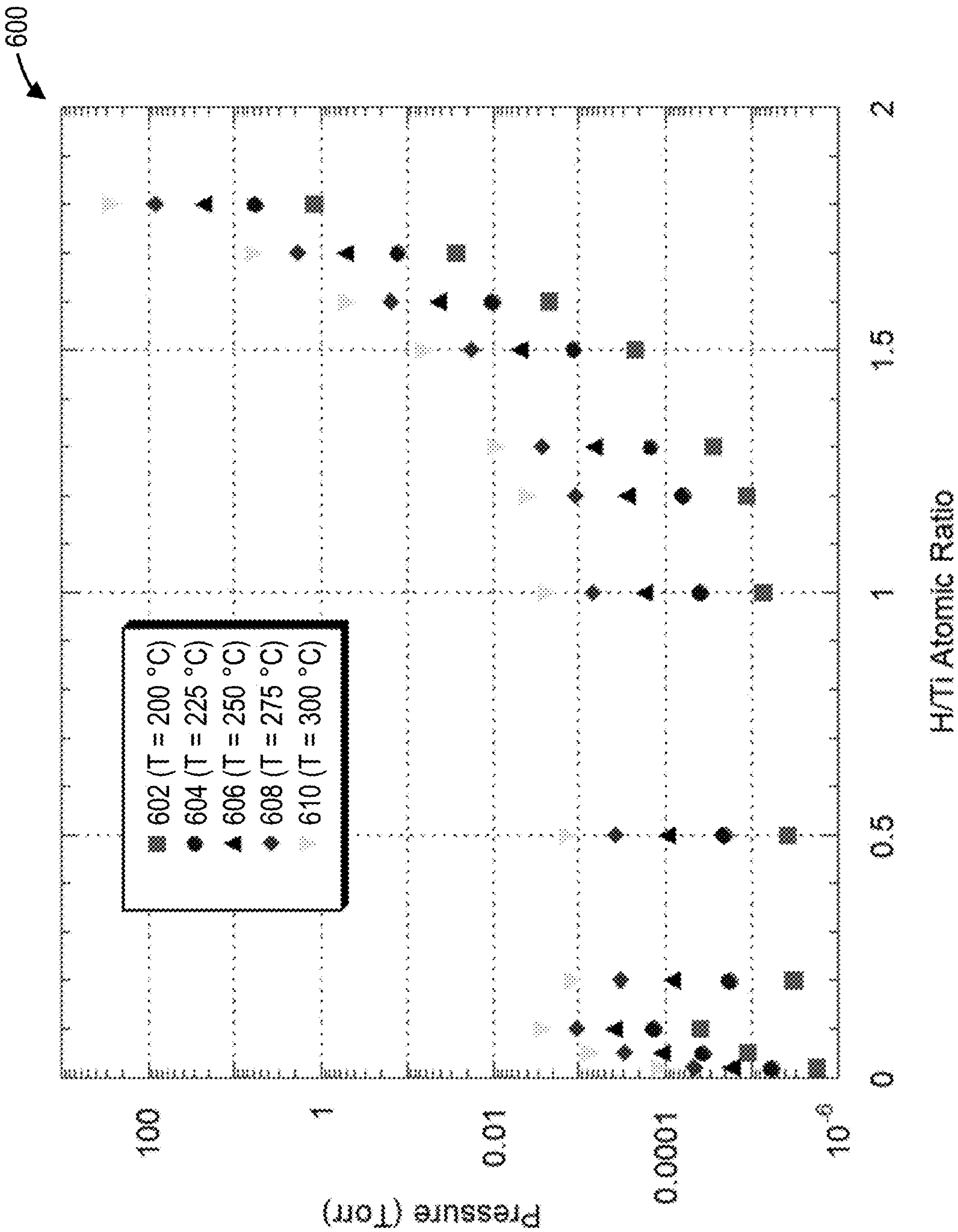
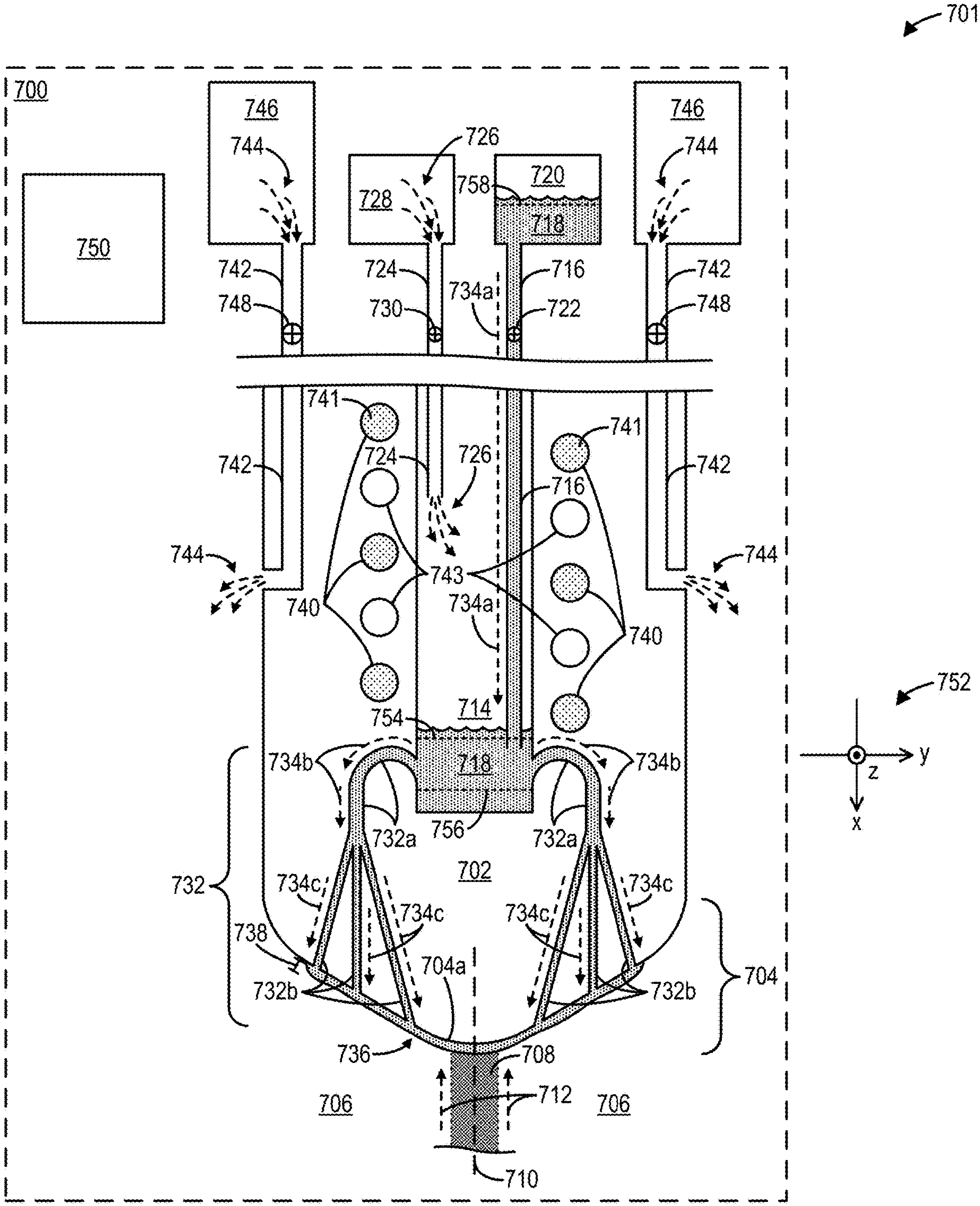

600
602 (T = 200 °C)
604 (T = 225 °C)
606 (T = 250 °C)
608 (T = 275 °C)
610 (T = 300 °C)
Pressure (Torr)
100
1
0.01
0.0001
10^{-6}
H/Ti Atomic Ratio
0
0.5
1
1.5
2

FIG. 7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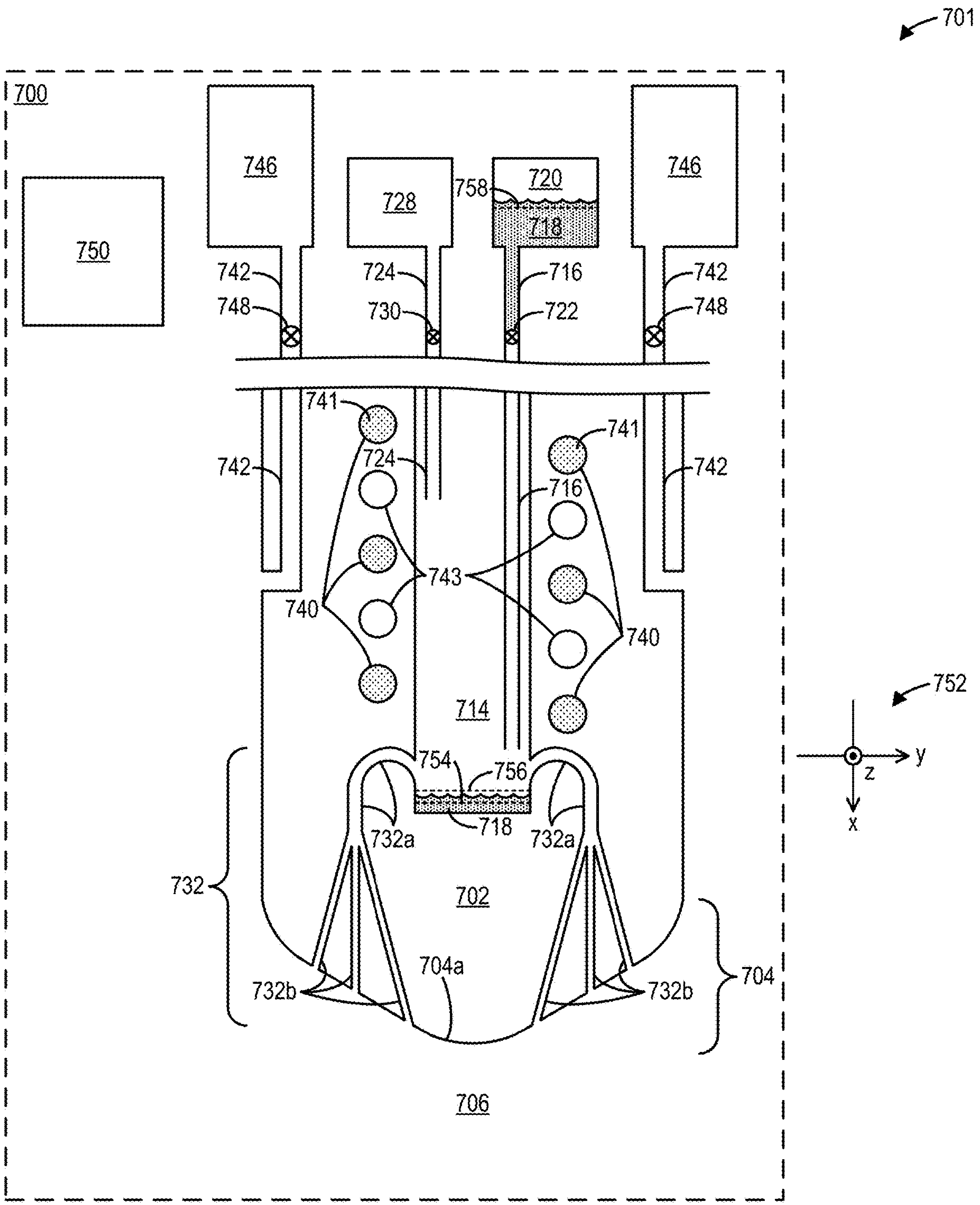
700
746
744
726
720
758
718
728
750
742
748
724
730
734a
716
722
741
743
740
714
754
756
734b
732a
702
732
734c
738
732b
704a
704
736
708
706
712
710
752
y
z
x

FIG. 8A


701
700
750
746
728
720
758
718
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742
724
716
742
748
730
722
748
741
741
742
724
716
742
743
740
740
714
752
y
z
x
754
756
718
732a
732a
732
702
704a
704
732b
732b
706

FIG. 8B

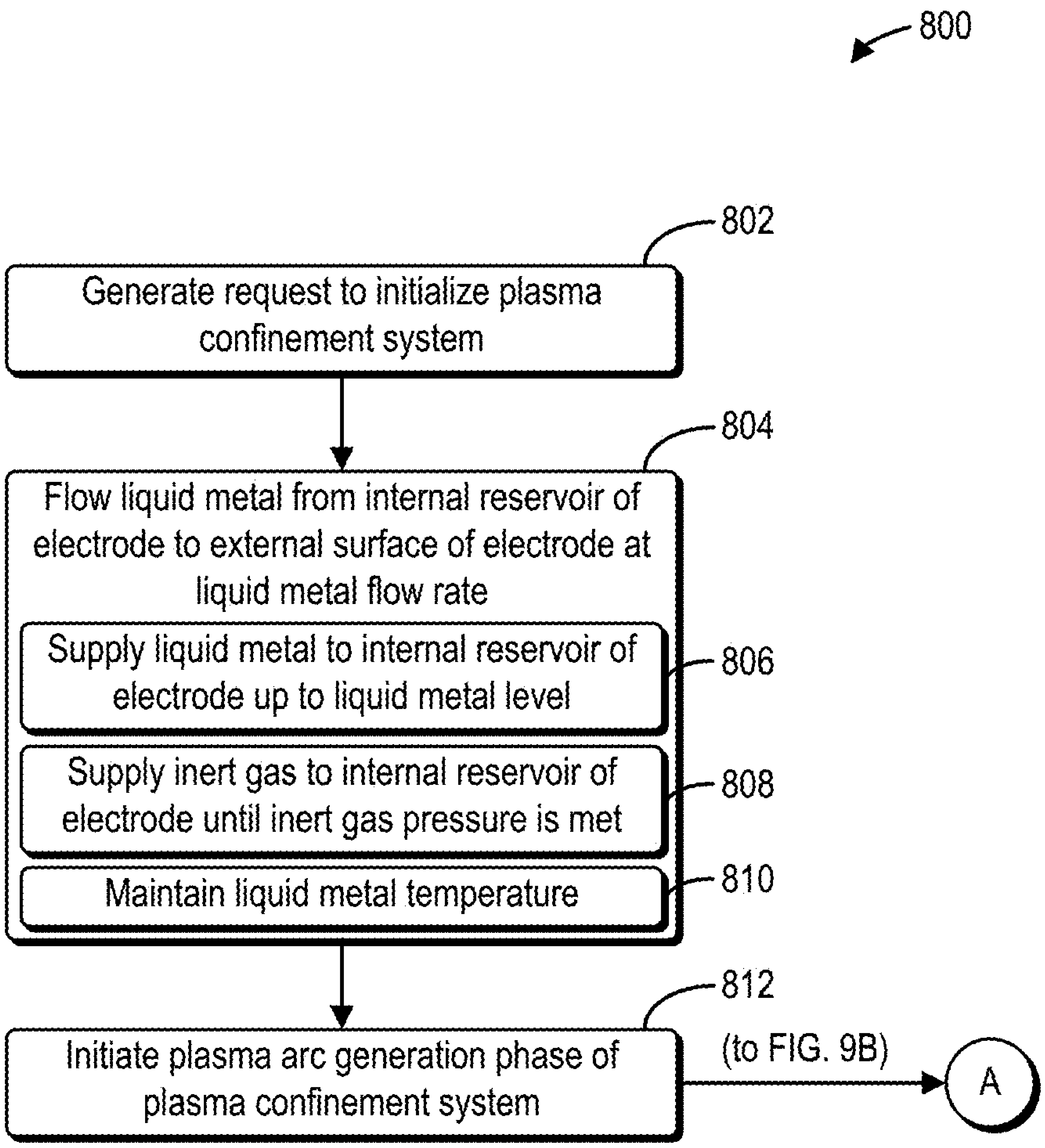
800
802
Generate request to initialize plasma confinement system
804
Flow liquid metal from internal reservoir of electrode to external surface of electrode at liquid metal flow rate
Supply liquid metal to internal reservoir of electrode up to liquid metal level
806
Supply inert gas to internal reservoir of electrode until inert gas pressure is met
808
Maintain liquid metal temperature
810
812
Initiate plasma arc generation phase of plasma confinement system
(to FIG. 9B)
A

FIG. 9A

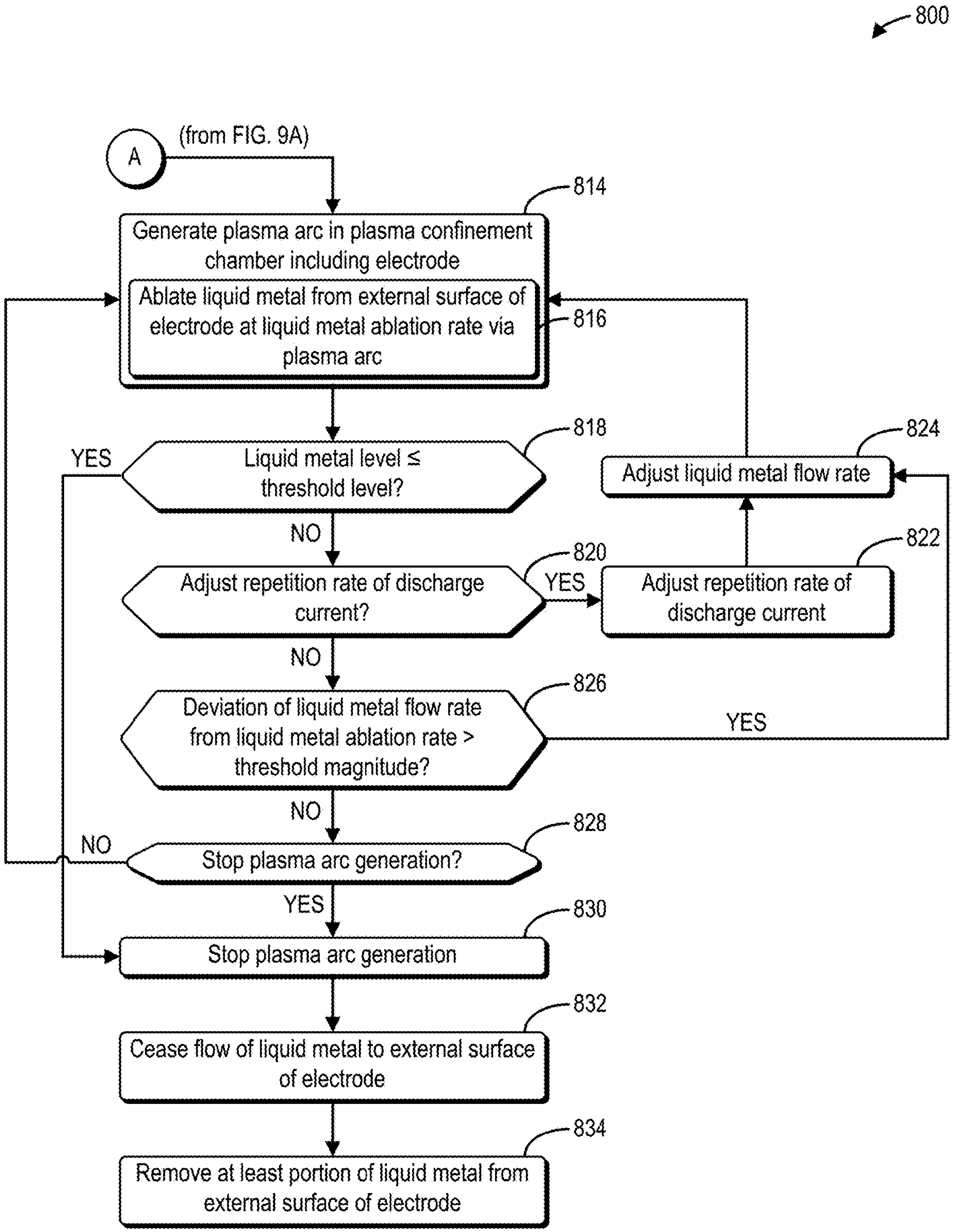
800
A
(from FIG. 9A)
814
Generate plasma arc in plasma confinement chamber including electrode
Ablate liquid metal from external surface of electrode at liquid metal ablation rate via plasma arc
816
818
Liquid metal level ≤ threshold level?
YES
NO
824
Adjust liquid metal flow rate
820
Adjust repetition rate of discharge current?
YES
822
Adjust repetition rate of discharge current
NO
826
Deviation of liquid metal flow rate from liquid metal ablation rate > threshold magnitude?
YES
NO
828
Stop plasma arc generation?
NO
YES
830
Stop plasma arc generation
832
Cease flow of liquid metal to external surface of electrode
834
Remove at least portion of liquid metal from external surface of electrode

FIG. 9B

ELECTRODE AND DECOMPOSABLE ELECTRODE MATERIAL FOR Z-PINCH PLASMA CONFINEMENT SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to each of U.S. Provisional Application No. 63/303,473, entitled "ELECTRODE AND DECOMPOSABLE ELECTRODE MATERIAL FOR Z-PINCH PLASMA CONFINEMENT SYSTEM" and filed on Jan. 26, 2022, and U.S. Provisional Application No. 63/303,477, entitled "IN SITU RENEWABLE ELECTRODE FOR Z-PINCH PLASMA CONFINEMENT SYSTEM" and filed on Jan. 26, 2022. The entire contents of each of the above-identified applications are hereby incorporated by reference for all purposes.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made, at least in part, with government support under Grant Nos. DE-AR001010 and DE-AR001260, awarded by the United States Department of Energy. The government has certain rights in the invention.

FIELD

[0003] Embodiments of the subject matter disclosed herein relate to methods and systems for plasma confinement to induce thermonuclear fusion reactions, and more particularly to electrode compositions and configurations for a Z-pinch plasma confinement system.

BACKGROUND

[0004] Economical, efficient, and self-sustainable fusion power has proven elusive. Even with continuing advances, an amount of electrical power input into a fusion reactor almost invariably outweighs electrical power output by the fusion reactor, especially in a production-scale design. A number of factors affect generation of self-sustaining, capturable fusion power or "fusion ignition." For example, fusion reactor configurations may be discussed in terms of the quality of plasma confinement within the fusion reactor, which may be quantified by the triple product of plasma density, plasma confinement time, and plasma temperature. Maximizing one or more factors of the triple product to obtain net fusion power output is particularly difficult.

[0005] One example reaction which may be utilized is fusion of deuterium and tritium nuclei, which may be given as:

$$^{2}H+^{3}H\rightarrow^{4}He+n \quad (1)$$

[0006] One complicating aspect introduced by the deuterium-tritium fusion reaction is the introduction of the free neutron byproduct n. In combination with electrical discharge currents (which bring about highly energetic ion flux during operation of the fusion reactor), free neutrons may erode material from surfaces of electrodes interfacing with a plasma confinement chamber. While reductions in the discharge current or a repetition rate of the discharge current may correspondingly reduce electrode erosion, net electrical power generation may also suffer such that fusion ignition may remain unattainable.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Various embodiments and techniques will be described with reference to the drawings, in which:

[0008] FIG. **1** shows a schematic cross-sectional diagram of a plasma confinement system including a plurality of electrodes, in accordance with at least one embodiment;

[0009] FIG. **2** shows a block diagram of a method for operating a plasma confinement system, for example, by initiating and driving a sheared ion velocity flow therein for stabilization of a Z-pinch discharge, in accordance with at least one embodiment;

[0010] FIGS. **3**A-**3**F show schematic cross-sectional diagrams of a process of initiating and driving a sheared ion velocity flow in the plasma confinement system of FIG. **1** for stabilization of a Z-pinch discharge, in accordance with at least one embodiment;

[0011] FIG. **4** shows a schematic cross-sectional diagram of a plasma confinement system including a plurality of electrodes, in accordance with at least one embodiment;

[0012] FIG. **5** shows a block diagram of a method for forming an electrode and operating a plasma confinement system therewith, in accordance with at least one embodiment;

[0013] FIG. **6** shows a plot of a plurality of ion implantation depths in titanium as a function of ion energy for example ions;

[0014] FIG. **7** shows a plot of a plurality of isothermal pressures as a function of H:Ti atomic ratio in example titanium hydrides;

[0015] FIG. **8**A shows a schematic cross-sectional diagram of an electrode in a plasma confinement chamber of a thermonuclear fusion reactor during operation thereof, in accordance with at least one embodiment;

[0016] FIG. **8**B shows a schematic cross-sectional diagram of the electrode of FIG. **8**A prior to or following operation of the thermonuclear fusion reactor, in accordance with at least one embodiment; and

[0017] FIGS. **9**A and **9**B show block diagrams of a method for operating a plasma confinement system including an in situ renewable electrode, in accordance with at least one embodiment.

DETAILED DESCRIPTION

[0018] Techniques described and suggested herein include a plasma confinement system that includes a plurality of electrodes, each electrode of the plurality of electrodes arranged coaxially with respect to an assembly region of the plasma confinement system and positioned so as to be exposed to the assembly region, wherein one or more electrodes of the plurality of electrodes includes an electrode material which releases hydrogen gas above a threshold temperature.

[0019] In some embodiments, a thermonuclear fusion reactor includes a plasma confinement chamber, an inner electrode, and an outer electrode at least partially surrounding the inner electrode, and wherein one or both of the inner electrode or the outer electrode includes a metal hydride to release a fuel gas between the inner electrode and the outer electrode to contribute plasma to a thermonuclear fusion process of the thermonuclear fusion reactor. For example, the one or both of the inner electrode or the outer electrode may include a section composed of the metal hydride.

[0020] In some examples, a method includes generating a thermonuclear fusion reaction in a thermonuclear fusion reactor by at least heating an electrode formed from a bulk material and a metal layer evaporated thereon, the metal layer loaded with deuterium and/or tritium, to cause the electrode to release hydrogen gas, forming, using the hydrogen gas, plasma inside the thermonuclear fusion reactor, and using electrical current directed into the plasma, via the electrode, to compress the plasma to produce the thermonuclear fusion reaction. For example, the metal layer may be composed of a metal hydride (e.g., a metal deuteride or a metal tritide or a combination thereof). The metal hydride may be formed following evaporation of the metal layer onto the bulk material and loading of the metal layer with the deuterium and/or tritium.

[0021] In at least one embodiment, a plasma confinement system includes a plasma confinement chamber, and an electrode body, including a nosecone positioned so as to be exposed to the plasma confinement chamber, an internal reservoir fluidly coupled to a liquid metal source which stores at least a portion of a liquid metal and/or supplies the liquid metal to the internal reservoir during operation of the plasma confinement system, and a plurality of internal liquid flow channels extending to a surface of the nosecone so as to fluidly couple the internal reservoir to the plasma confinement chamber.

[0022] A thermonuclear fusion reactor in accordance with various embodiments includes a plasma confinement chamber, an electrode at least partially enclosed within the plasma confinement chamber, the electrode including a nosecone which intersects with an axis of a plasma arc confined within the plasma confinement chamber during operation of the thermonuclear fusion reactor, and a liquid metal meniscus formed on a surface of the nosecone, the liquid metal meniscus directly interacting with the confined plasma arc during operation of the thermonuclear fusion reactor.

[0023] A method in accordance with various embodiments includes flowing a liquid metal from an internal reservoir of an electrode to an external surface of the electrode at a liquid metal flow rate, generating a confined plasma arc to ablate the liquid metal from the external surface at a liquid metal ablation rate, and responsive to the liquid metal flow rate deviating from the liquid metal ablation rate by greater than a threshold magnitude, adjusting the liquid metal flow rate by adjusting one or more of a liquid metal level in the internal reservoir, an inert gas pressure in the internal reservoir, or a liquid metal temperature.

[0024] These, as well as other aspects, advantages, and alternatives will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings. Further, it should be understood that descriptions and figures provided herein are intended to illustrate the invention by way of example only and, as such, that numerous variations are possible.

[0025] For example, the following description relates to various embodiments of systems and methods for confining a plasma within a fusion reactor to sufficient temperature and sufficient density for sufficient duration to induce thermonuclear fusion. In some embodiments, output from the thermonuclear fusion may be harnessed for energy generation/storage. However, other use cases are envisioned for the disclosed embodiments or variations thereof, such as propulsion (e.g., for space vehicles, aircraft, watercraft and submersibles, etc.), research, etc. In extreme environments (e.g., reduced gravity environments aboard space vehicles), certain modifications may be made, e.g., to maintain performance. For example, though the liquid metal meniscus may be retained to the surface of the nosecone via surface tension and/or capillary action, additional components may be implemented to prevent ablated metal from interfering with the confined plasma arc. As an example, a mechanical plunger may be included which may induce flow of the liquid metal from the internal reservoir to the surface of the nosecone, as well as in a reverse direction (from the surface of the nosecone to the internal reservoir, in a similar operating principle to a hypodermic syringe). However, in certain embodiments, retaining tighter tolerances for the mechanical plunger may be complicated by higher temperatures and swelling from neutronic flux.

[0026] In an example embodiment, plasma confinement may be achieved via a Z-pinch configuration, wherein an electric current (also known as the “Z-pinch discharge current” or “pinch current”) is discharged through the plasma to generate a magnetic field which compresses or “pinches” the plasma in along an axis (e.g., along a linear path through an assembly region of a plasma confinement chamber). The electric current is discharged between a pair of electrodes, which may be subject to appreciable rates of ionic, electronic, and/or neutronic bombardment during fusion reactor operation. As a result, one or more electrodes within the plasma confinement chamber may degrade or erode (e.g., lose mass) over lifetime use of the fusion reactor.

[0027] At production scale, a repetition rate of electrical discharge within the plasma confinement chamber may be on the order of tens of Hertz. In one example, based on known spark gap erosion rates (which may approximate erosion within Z-pinch configurations), discharge currents sufficient to induce desirable plasma confinement at a repetition rate of 10-11 Hz may result in hundreds of grams of carbon electrode erosion per hour. Such severe electrode erosion may limit a lifetime of a continuously operating fusion reactor to well under a month.

[0028] Of particular, non-limiting interest is maintaining stable (e.g., with little or no appreciable degradation) interfaces between the electrodes and a confined plasma arc within the plasma confinement chamber and/or improving overall fusion reactor performance. At least two strategies are envisioned herein, which may be implemented in isolation in some embodiments and in combination in other embodiments: (i) forming a static solid electrode from an electrode material which supports or improves fusion reactor performance (e.g., as compared to carbon); and (ii) forming an in situ renewable electrode to prevent degradation of a bulk interior of the electrode.

[0029] As to formation of the static solid electrode, performance improvements from electrode materials selected for degradation resistance alone may be limited to suborders of magnitude. Thus, electrode materials which confer additional benefits or otherwise improve conditions within the plasma confinement chamber for thermonuclear fusion may be desirable. In an example embodiment, an electrode, or at least a portion thereof, may be formed from one or more metallic hydrides. A given metallic hydride may be considered a two-phase system in reversible equilibrium, as governed by the following:

$$2/n\mathrm{M}+\mathrm{H}_2 \leftrightarrow 2/n\mathrm{MH}_n \quad (2)$$

where n is a ratio of hydrogen atoms to metal ions M in the solid phase. When M is exposed to H_2, the metal hydride MH_n may be spontaneously formed in an exothermic process. Upon input of heat, MH_n may decompose back to M and H_2. As such, MH_n may provide an internal gas source under plasma confinement conditions, which may supplement or entirely substitute valves (so-called "puff valves") introducing additional gaseous fuel into the plasma confinement chamber.

[0030] Moreover, since MH_n may be formed with deuterium (^2H or D) and/or tritium (^3H or T) (e.g., via reaction of M with D_2 and/or T_2), electrodes formed from metal deuterides and/or metal tritides (e.g., MD_lT_m, where l+m=n) may directly participate in thermonuclear fusion reactions (e.g., reaction (1)) in the plasma confinement chamber upon ionic bombardment of the electrodes. As such, MH_n may provide an additional source of fusion neutrons (e.g., as a byproduct of deuterium-tritium fusion).

[0031] In certain embodiments, MH_n may itself consume free neutrons to provide an internal tritium source. For example, lithium deuteride (^6LiD) may be used as a source of tritium ("tritium breeding"):

$$^6Li^2H+n\rightarrow{}^4He+{}^3H+{}^2H \qquad (3)$$

[0032] In some embodiments, tritium sourced via reaction (3) may provide an internal supplement to an external tritium source (e.g., a tritium breeding blanket, such as a lithium-containing ceramic or a circulating liquid metal wall such as lead-lithium; such configurations may also function as an electrode, for example, replacing the outer electrode **304** of FIG. **1**).

[0033] As such, one technical effect of using one or more metal hydrides (e.g., metal deuterides and/or metal tritides) as an electrode material is that the electrode itself may interact with the confined plasma arc to supplement or increase thermonuclear fusion within the plasma confinement chamber of the fusion reactor.

[0034] In addition or alternative to adjusting a composition or preparation of a static solid bulk or composite body of the electrode, an interface where the electrode and the assembly region are directly coupled (e.g., without any intervening components or volumes) to one another may be continuously renewed so as to form the in situ renewable electrode (as used herein, "interface" or "interface with" may refer to a solid-gas or liquid-gas phase boundary whereat the solid phase or the liquid phase is in direct contact with the gas phase). As an example, the interface may include a continuously fed (e.g., fed without interruption, or with no appreciable delay, during fusion reactor operation) or dynamically fed (e.g., responsively fed so as to maintain a predetermined thickness at the interface) solid at a surface of the electrode. As another example, the interface may include a continuously fed or dynamically fed liquid meniscus at the surface of the electrode. As another example, a gas may be continuously or dynamically regenerated between the surface of the electrode and the assembly region.

[0035] In an example embodiment, a liquid metal film may be maintained on a nosecone of the electrode at a predetermined thickness responsive to adjustments to a repetition rate of the discharge current and/or a rate of electrical power generation. More specifically, the predetermined thickness may be dynamically maintained via adjustments to a flow rate of the liquid metal from an internal reservoir within the electrode body to a surface of the nosecone. As an example, the flow rate may be maintained less than an upper threshold flow rate above which excess liquid metal may form into droplets and separate from the surface of the nosecone, which may adversely affect the confined plasma arc. As an additional or alternative example, the flow rate may be maintained greater than a lower threshold flow rate below which insufficient liquid metal may be present on the surface of the nosecone and appreciable electrode erosion may result. In an example embodiment, each of the upper and lower threshold flow rates may be dependent on the repetition rate of the discharge current and/or the rate of electrical power generation such that the flow rate of the liquid metal, being maintained between the upper and lower threshold flow rates, may match a rate of liquid metal ablation from the surface of the nosecone.

[0036] As such, one technical effect of supplying and dynamically replenishing the liquid metal on the nosecone is that the liquid metal may erode and be replaced during fusion reactor operation, such that erosion of the body of the electrode may be mitigated or altogether obviated and a fusion reactor including the electrode may continuously operate for a year or more without replacement of the electrode.

[0037] Although example embodiments described in detail below with reference to FIGS. **1-9**B may include isolated discussions of the static, solid electrode including the metal hydride or the in situ renewable electrode including the liquid metal film, in other embodiments, an electrode (e.g., an inner electrode, an outer electrode, or an intermediate electrode) including a static, solid electrode body including a metal hydride may be formed with a liquid metal film dynamically replenished on a nosecone of the electrode body. In alternative embodiments, a first electrode (e.g., an outer electrode or an intermediate electrode) of the fusion reactor may be a static, solid electrode including the metal hydride and another, second electrode (e.g., an inner electrode) of the fusion reactor may be an in situ renewable electrode including a nosecone or other surface and a liquid metal film dynamically replenished on the nosecone or other surface. In such embodiments, the second electrode may intersect with the confined plasma arc, the liquid metal film being provided on the nosecone or other surface of the second electrode to mitigate or altogether obviate erosion of a body of the second electrode.

[0038] Moreover, in additional, alternative, or otherwise modified embodiments to those described in detail below with reference to FIGS. **1-9**B, one or more components of the plasma confinement system may be added, removed, substituted, modified, or interchanged to adapt the plasma confinement system for a given use case. As an example, a plasma may be directly injected into a plasma confinement chamber of the plasma confinement system, e.g., in addition to or instead of intrachamber conversion of a fuel gas to the plasma. Further, though various embodiments described herein are discussed with reference to Z-pinch plasma confinement, the various embodiments, with or without modification, may be applicable to other types of thermonuclear fusion reactors and plasma confinement systems which compress, react, or otherwise use plasma.

[0039] Referring now to FIG. **1**, a schematic cross-sectional diagram of a plasma confinement system **300**, such as may be included within a thermonuclear fusion reactor, is shown. The plasma confinement system **300** may generate a plasma arc within an assembly region **326** of a plasma confinement chamber **340**, the plasma arc confined, compressed, and sustained by an axially symmetric magnetic field. The axially symmetric magnetic field may be stabilized by a sheared ion velocity flow driven by electrical discharge between a pair of electrodes interfacing with the plasma confinement chamber **340**. FIGS. **2**-**3**F discuss further operational details of the plasma confinement system **300**. One or more aspects of the plasma confinement system **300** may be readily transferable to other plasma confinement configurations, such as plasma confinement system **900** described in detail below with reference to FIG. **4**.

[0040] In one embodiment, at least one of the pair of electrodes is a static, solid electrode including an electrode material **346** which supplements or increases thermonuclear fusion within the plasma confinement chamber **340** during generation of the plasma arc. For instance, the electrode material **346** may release hydrogen gas above a threshold temperature, e.g., to supply fuel gas for the plasma arc. As an example composition, the electrode material **346** may be a metal hydride, such as a metal deuteride and/or a metal tritide including one or more of titanium (Ti), zirconium (Zr), scandium (Sc), magnesium (Mg), vanadium (V), lithium-6 (^{6}Li), or alloys formed by any combination of one or more of the preceding metals. A method for forming such a metal hydride containing electrode and operating a plasma confinement system therewith is discussed in detail below with reference to FIG. **5**. Ion implantation curves and isotherms for an example metal hydride are provided in FIGS. **6** and **7**, respectively.

[0041] In an additional or alternative embodiment, at least one of the pair of electrodes may be an in situ renewable electrode including a protective film of a flowing, liquid metal which may ablate from an external surface of the electrode upon interaction with the plasma arc and thereby mitigate high-discharge erosion of the external surface. Additional features of such an in situ renewable electrode are discussed in detail below with reference to FIGS. **8**A and **8**B, and a method of operating a plasma confinement system including the in situ renewable electrode is discussed in detail below with reference to FIGS. **9**A and **9**B.

[0042] A set of Cartesian coordinate axes **152** is shown in FIG. **1** for contextualizing positions of the various components of the plasma confinement system **300** and for comparing between the various views of FIGS. **1** and **3**A-**3**F. Specifically, x-, y-, and z-axes are provided which are mutually perpendicular to one another, where the x- and y-axes define a plane of the schematic cross-sectional diagram shown in FIG. **1** and the z-axis is perpendicular thereto. In some embodiments, a direction of gravity may be parallel to and coincident with any direction in the plane of the schematic cross-sectional diagram of FIG. **1**. For example, the direction of gravity may be parallel and coincident with a positive direction of the x-axis. In additional or alternative embodiments, the direction of gravity may be within a plane defined by the y- and z-axes (e.g., parallel and coincident with a negative direction of the y-axis).

[0043] In an example embodiment, the plasma confinement system **300** may include an inner electrode **302** and an outer electrode **304** that substantially surrounds the inner electrode **302** (when the term "substantially" is used herein, it is meant that the recited characteristic, parameter, or value need not be achieved exactly, but that deviations or variations, including, for example, tolerances, measurement error, measurement accuracy limitations, and other factors known to those of skill in the art, may occur in amounts that do not preclude the effect the characteristic was intended to provide). For example, the inner electrode **302** may be at least partially circumferentially surrounded by the outer electrode **304**, such that one end of the inner electrode **302** (e.g., a first end **318**) may be partially or fully surrounded by the outer electrode **304**. In some embodiments, the inner electrode **302** may have a length (e.g., parallel with the y-axis and between the first end **318** and an opposing second end **320**) ranging from 25 cm to 1 m or more and a radius (e.g., parallel with the x-axis) ranging from 2 cm to 1 m, and the outer electrode **304** may have a length (e.g., parallel with the y-axis and between a first end **322** and an opposing second end **324**) ranging from 50 cm to 6 m, a radius (e.g., parallel with the x-axis) ranging from 6 cm to 2 m or more, and an annular thickness (e.g., along the x-axis) ranging from 6 mm to 12 mm.

[0044] In certain embodiments, and as shown in FIG. **1**, the plasma confinement system **300** may further include an intermediate electrode **303** that faces the inner electrode **302**. In other embodiments, and as described in detail below with reference to FIG. **4**, the intermediate electrode **303** may substantially surround the inner electrode **302** and the outer electrode **304** may substantially surround the intermediate electrode **303**. For example, the inner electrode **302** may be at least partially circumferentially surrounded by the intermediate electrode **303** and the intermediate electrode **303** may be at least partially circumferentially surrounded by the outer electrode **304**, such that one end of the inner electrode **302** (e.g., the first end **318**) may be partially or fully surrounded by the intermediate electrode **303** and one end of the intermediate electrode **303** may be partially or fully surrounded by the outer electrode **304**.

[0045] In some embodiments, the plasma confinement chamber **340** may be a physical structure inclusive of a volume delimited by one or more electrodes, insulators, and internal components of the plasma confinement system **300**. As such, in certain embodiments, the plasma confinement chamber **340** may include the one or more electrodes, insulators, and internal components of the plasma confinement system **300** which delimit the volume of the plasma confinement chamber **340**.

[0046] In an example embodiment, the outer electrode **304** may define a radial outer boundary of the plasma confinement chamber **340**. In one example, the radial outer boundary may be cylindrical and formed as a circular cross section propagated along the x-axis, the circular cross section parallel to a plane formed by the y- and z-axes. The plasma confinement chamber **340** may be partitioned (e.g., without any physical partition) into: an acceleration region **310** between the inner electrode **302** and the outer electrode **304**, and the assembly region **326** between the first end **318** of the inner electrode **302** and the intermediate electrode **303**. Alternatively, in embodiments where the intermediate electrode **303** at least partially surrounds the inner electrode **302**, the acceleration region **310** may be between the inner electrode **302** and the intermediate electrode **303**, and the assembly region **326** may be between the first end **318** of the inner electrode **302** and an opposing end of the outer electrode **304**. In either case, the plasma confinement system **300** may include a plurality of electrodes (e.g., the inner electrode **302**, the intermediate electrode **303**, and the outer electrode **304**), each electrode of the plurality of electrodes arranged coaxially with respect to the assembly region **326** (e.g., parallel to the x-axis) and positioned so as to be exposed to the assembly region **326** (e.g., each given electrode of the plurality of electrodes may interface with a volume of the assembly region **326** without any intervening components or volumes, such that an electrical current can pass directly from a confined plasma to the given electrode). More specifically, the outer electrode **304** may be positioned to define at least a portion of an outer boundary of the assembly region **326**, the inner electrode **302** may be positioned at one end of the assembly region **326** (e.g., coincident with the first end **318** of the inner electrode **302**), and the intermediate electrode **303**, when included, may be positioned at the same end of the assembly region **326** with respect to the inner electrode **302** or an opposite end of the assembly region **326** with respect to the inner electrode **302**. The plasma confinement system **300** may be configured to sustain a Z-pinch plasma (e.g., the plasma arc) within the assembly region **326** as described below. In some embodiments, the acceleration region **310** may have a length (e.g., parallel with the y-axis and between the second end **324** of the outer electrode **304** and the first end **318** of the inner electrode **302**) ranging from 25 cm to 1.5 m and an annular thickness ranging from 2 cm to 10 cm, and the assembly region **326** may have a length (e.g., parallel with the y-axis and between the first end **318** of the inner electrode **302** and the first end **322** of the outer electrode **304**) ranging from 25 cm to 3 m.

[0047] The plasma confinement system **300** may include one or more first valves **306** configured to direct gas from within the inner electrode **302** to the acceleration region **310** and one or more second valves **312** configured to direct gas from outside the outer electrode **304** to the acceleration region **310**. The gas may be the fuel gas, which may be utilized to form the plasma arc upon release of the gas into the plasma confinement chamber **340** and application of the discharge current. As used herein, "fuel gas" may refer to any species utilized to form the plasma arc. As such, the fuel gas may include neutral gas species, such as dihydrogen [e.g., hydrogen (H_2), deuterium (D_2), and/or tritium (T_2)], ^3He, ^6Li, ^{11}B, etc., and/or pre-ionized gas species (e.g., such as introduced via "direct plasma injection" or "plasma injection" configurations).

[0048] The plasma confinement system **300** may include a first power supply **314** configured to apply a voltage (e.g., ranging from 2 kV to 50 kV in some examples or from 1 kV to 40 kV in other examples) between the inner electrode **302** and the outer electrode **304**. In some embodiments, the plasma confinement system **300** may further include a second power supply **315** configured to apply a voltage (e.g., ranging from 2 kV to 50 kV in some examples or from 1 kV to 40 kV in other examples) between the inner electrode **302** and the intermediate electrode **303**. In certain embodiments, the plasma confinement system **300** may operate with only one of the first and second power supplies **314**, **315**. In other embodiments, the plasma confinement system **300** may operate at least with both of the first and second power supplies **314**, **315**. In some embodiments, one or both of the first and second power supplies **314**, **315** may include a switching pulsed direct current (switching pulsed-DC) power supply including an energy source (e.g., a capacitor bank), a switch (e.g., a spark gap, an ignitron, or a semiconductor switch), and a pulse shaping network (including, e.g., inductors, resistors, diodes, and the like). In some embodiments, one or both of the first and second power supplies **314**, **315** may be voltage-controlled. In other embodiments, one or both of the first and second power supplies **314**, **315** may be current-controlled. In some embodiments, other suitable types of power supplies may be used as one or both of first and second power supplies **314**, **315**, including DC and alternating current (AC) power supplies (e.g., DC grids, voltage source converters, homopolar generators, and the like).

[0049] The inner electrode **302** may include an electrically conducting (e.g., stainless steel) shell having a modified cylindrical body **316** (e.g., a substantially cylindrical body with a tapered, rounded base at the first end **318**). Specifically, the inner electrode **302** may include the first end **318** (e.g., a tapered, rounded base) and the opposing second end **320** (e.g., a substantially flat, circular base). For instance, the inner electrode **302** may include a nosecone **344** positioned at the first end **318**, the nosecone **344** exposed to the assembly region **326** so as to be intersected by an axis of the confined plasma arc coaxial with each electrode of the plurality of electrodes (e.g., parallel to the x-axis). In an example embodiment, the nosecone **344** may include the electrode material **346** which supplements or increases thermonuclear fusion within the plasma confinement chamber **340** during generation of the plasma arc (e.g., via release of hydrogen gas to fuel the confined plasma arc). However, in other embodiments, the electrode material **346** is not limited to the nosecone **344** and may additionally be included on another portion of the inner electrode **302** and/or on any other electrode(s) of the plurality of electrodes (accordingly, in certain embodiments, the electrode material **346** may not be included on the nosecone **344** at all). In any case, the electrode material **346** may only occupy a portion of one or more electrodes of the plurality of electrodes and a remaining portion (e.g., all portions of the plurality of electrodes excepting the portion occupied by the electrode material **346**) may be free from the electrode material **346**. Accordingly, when the electrode material **346** is included, fuel gas may be expelled into the acceleration region **310** responsive to heating one or more of the inner electrode **302**, the intermediate electrode **303**, or the outer electrode **304** (e.g., such that the electrode material **346** thermally decomposes to release the fuel gas). The inner electrode **302** may further include one or more conduits or channels **342** for routing gas (e.g., the fuel gas) from the one or more first valves **306** to the acceleration region **310**, for example, during operation of the plasma confinement system **300** to generate thermonuclear fusion.

[0050] In additional or alternative embodiments, the electrode material **346** may be present as a filament separate from any of the electrodes in the plasma confinement system **300**. In such embodiments, the electrode material **346** may, upon heating and thermal decomposition thereof, provide at least a portion of the fuel gas to the plasma confinement chamber **340**.

[0051] The outer electrode **304** may include an electrically conducting (e.g., stainless steel) shell having a substantially cylindrical body **328**. Specifically, the outer electrode **304** may include the first end **322** (e.g., a substantially flat, circular base) and the opposing second end **324** (e.g., a substantially flat, circular base). The outer electrode **304** may surround much (e.g., a majority) of the inner electrode **302**. In an example embodiment, the inner electrode **302** and the outer electrode **304** may be concentric and have radial symmetry with respect to the x-axis. The first end **318** of the inner electrode **302** may be between the first end **322** of the outer electrode **304** and the second end **324** of the outer electrode **304**. The outer electrode **304** may further include one or more conduits or channels (not shown at FIG. **1**) for routing gas (e.g., the fuel gas) from the one or more second valves **312** to the acceleration region **310**, for example, during operation of the plasma confinement system **300** to generate thermonuclear fusion.

[0052] The intermediate electrode **303** may include an electrically conducting material (e.g., stainless steel). In some embodiments, the intermediate electrode **303** may be substantially disc-shaped. In other embodiments, the intermediate electrode may have a substantially cylindrical body concentric with each of the inner electrode **302** and the outer electrode **304** and having radial symmetry with respect to the x-axis.

[0053] The one or more first valves **306** may take the form of so-called "puff valves" (e.g., operable to provide fuel gas for formation of a plasma or increase a density of the as-generated plasma arc via gas puffing) or plasma injectors. In additional or alternative embodiments, the one or more first valves **306** may include at least one electrically actuated valve, such as a solenoid-driven valve. However, the one or more first valves **306** are not limited to such configurations and may include any type of valve configured to direct gas (e.g., H_2, D_2, T_2) from within the inner electrode **302** to the acceleration region **310**.

[0054] In some embodiments, the one or more first valves **306** may include at least one gas-puff valve (e.g., to provide neutral gas to the acceleration region **310**) and/or at least one plasma injector (e.g., to provide pre-ionized gas to the acceleration region **310**) installed as a regular array or arrays along the inner electrode **302** (e.g., regularly distributed around a central axis of the acceleration region **310**). As shown in FIG. **1**, the one or more first valves **306** may be positioned (e.g., positioned axially) between the first end **318** of the inner electrode **302** and the second end **320** of the inner electrode **302**. Alternatively, the one or more first valves **306** may be located at (e.g., directly adjacent to) the first end **318** of the inner electrode **302** or the second end **320** of the inner electrode **302**. In FIG. **1**, each of the one or more first valves **306** is arranged within (e.g., positioned inside and on an inner surface of) the inner electrode **302**, but other examples are possible (e.g., positioned outside and on an outer surface of the inner electrode **302**). The one or more first valves **306** may be electrically actuatable in that the one or more first valves **306** may be operated by providing the one or more first valves **306** with a control voltage, as described below. In certain embodiments wherein the electrode material **346** is included, no first valves **306** may be included (e.g., the electrode material **346** may supply at least some of the gas upon decomposition thereof).

[0055] In an example embodiment, the acceleration region **310** may have a substantially annular cross section defined by the shapes of the inner electrode **302** and the outer electrode **304**. Specifically, the inner electrode **302** may define a radial inner boundary of the acceleration region **310** and the outer electrode **304** may define a radial outer boundary of the acceleration region **310**. In one example, each of the radial inner boundary and the radial outer boundary may be cylindrical and formed as a circular cross section propagated along the x-axis, the circular cross section parallel to the plane formed by the y- and z-axes. In other embodiments, the substantially annular cross section of the acceleration region **310** may be defined by the shapes of the inner electrode **302** and the intermediate electrode **303** (e.g., the inner electrode **302** may defined the radial inner boundary and the intermediate electrode **303** may define the radial outer boundary).

[0056] In the same manner as the one or more first valves **306**, the one or more second valves **312** may take the form of "puff valves" or plasma injectors. In additional or alternative embodiments, the one or more second valves **312** may include at least one electrically actuated valve, such as a solenoid-driven valve. However, the one or more second valves **312** are not limited to such configurations and may include any type of valve configured to direct gas (e.g., H_2, D_2, and/or T_2) from outside the outer electrode **304** (or the intermediate electrode **303**) to the acceleration region **310**.

[0057] In some embodiments, the one or more second valves **312** may include at least one gas-puff valve (e.g., to provide neutral gas to the acceleration region **310**) and/or at least one plasma injector (e.g., to provide pre-ionized gas to the acceleration region **310**) installed as a regular array or arrays along the outer electrode **304** (e.g., regularly distributed around the acceleration region **310**). As shown in FIG. **1**, the one or more second valves **312** may be positioned (e.g., positioned axially) between the first end **322** of the outer electrode **304** and the second end **324** of the outer electrode **304**. Alternatively, the one or more second valves **312** may be located at (e.g., directly adjacent to) the first end **322** of the outer electrode **304** or the second end **324** of the outer electrode **304**. In FIG. **1**, each of the one or more second valves **312** is arranged around (e.g., positioned outside and on an outer surface of) the outer electrode **304**, but other examples are possible (e.g., positioned within the plasma confinement chamber **340**, such as on an inner surface of the outer electrode **304** or on an inner surface of the intermediate electrode **303**). Moreover, in FIG. **1**, each of the one or more first valves **306** is axially aligned with each of the one or more second valves **312**, but other examples are possible. The one or more second valves **312** may be electrically actuatable in that the one or more second valves **312** may be operated by providing the one or more second valves **312** with a control voltage, as described below. In certain embodiments wherein the electrode material **346** is included, no second valves **312** may be included (e.g., the electrode material **346** may supply at least some of the gas upon decomposition thereof).

[0058] In some embodiments, gas-puff valves and/or plasma injectors included in the one or more first valves **306** and/or the one or more second valves **312** may be electronically triggered to independently deliver a "puff" of filling neutral and/or pre-ionized gas for a duration lasting up to several hundred μs (e.g., up to 1 ms). An amount of filling gas (also referred to herein as "fuel gas") delivered (e.g., in the "puff") may also be controlled by adjustments of a filling gas pressure supplied to the gas-puff valves and/or plasma injectors (e.g., to individual or all of the gas-puff valves and/or plasma injectors or subsets thereof). In addition, different gas-puff valves and/or plasma injectors (or different combinations of multiple gas-puff valves and/or plasma injectors) may be fed by different fill gas mixtures having, for example, different elemental ratios of filling gases and/or different isotopic ratios (e.g., adjustable D_2/T_2 molecular ratios). In some embodiments, the gas-puff valves and/or plasma injectors may be uniform (e.g., all of the same type/size with substantially the same operational settings). In other embodiments, different gas-puff valves and/or plasma injectors may be used for different locations. In additional or alternative embodiments, the gas-puff valves and/or plasma injectors may control a flow of gas into the acceleration region **310** via a manifold including multiple ports providing passage into the acceleration region **310**. In such embodiments, the ports of the manifold may be uniform or may vary in configuration (e.g., to deliver different amounts of gas to different locations of the acceleration region **310** when a respective gas-puff valve or plasma injector is open).

[0059] Similar to neutral gas injection via gas-puff valves, (pre-)ionized gas or plasma may be injected using combinations or manifolds of variously located plasma injectors fluidically coupled to respective plasma generators or guns which generate the plasma prior to injection into the acceleration region **310**. In some embodiments, the plasma may be sourced from a gas-injected washer plasma gun and/or a plasma thruster (e.g., a Hall effect thruster or a magnetohydrodynamic thruster), or, if the plasma is magnetized, from a high-power helicon plasma source, a radio frequency plasma source, a plasma torch, and/or a laser-based plasma source. Plasmas formed from gas mixtures may also be created and injected in a manner similar to neutral gas injection. Plasma injection may provide a finer control of an eventual axial plasma distribution as well as a shear flow profile thereof, which in turn may allow for higher fidelity control of plasma stability and lifetime. Additional control of plasma injection may be provided due to the plasma particles being charged particles that may be accelerated by electric fields created by a variable electrical bias (or voltage) on injection electrodes. Thus, a speed of the injected plasma may be finely controlled to allow for fine adjustment and optimization of breakdown of any neutral gas present (e.g., in the acceleration region **310**). Moreover, the injected plasma may travel at faster velocities than injected neutral gas, which may travel in a nearly static fashion (relative to the injected plasma) during Z-pinch discharge pulses. As such, relative to neutral gas injection, plasma injection may provide pre-ionized fuel "on demand" (e.g., more immediately), for example, to replenish the fuel gas during Z-pinch discharge pulses.

[0060] In some embodiments, the pre-ionized gas may be generated as an unmagnetized plasma, e.g., so as to avoid interaction between a magnetic field of the pre-ionized gas and a magnetic field of the acceleration region **310**. In other embodiments, the pre-ionized gas may be generated as a magnetized plasma, e.g., so as to align the magnetic field of the pre-ionized gas to be parallel with the magnetic field of the acceleration region **310** and/or be adjustable to provide a desired magnetic flux profile at an injection point of the pre-ionized gas.

[0061] In some embodiments, plasma to be injected into the acceleration region **310** may be generated by pre-ionizing neutral gas with a spark plug or via inductive ionization. More broadly, the gas-puff valves and/or plasma injectors may include one or more electrode plasma injectors and/or one or more electrodeless plasma injectors. In examples wherein the one or more electrode plasma injectors are included, the plasma to be injected into the acceleration region **310** may be generated, at least in part, by electrode discharge. In additional or alternative examples wherein the one or more electrodeless plasma injectors are included, the plasma to be injected into the acceleration region **310** may be generated, at least in part, by inductive discharge produced by an external coil window (e.g., a radio-frequency antenna operating at 400 kHz, 13.56 MHz, 2.45 GHz, and/or other frequencies permitted for use in a given local jurisdiction, such as within frequency ranges permitted by the Federal Communications Commission). In some embodiments, neutral gas for pre-ionization may be limited by a configuration of a neutral gas reservoir (e.g., a gas source **330**) and/or neutral gas conductance to a selected plasma injector configuration.

[0062] In some embodiments, axial distribution of the injected plasma may be ensured via an axisymmetric plasma injector configuration. In at least one embodiment, eight plasma injectors may be respectively positioned at eight equally spaced ports of the manifold. The eight ports may each be configured at an oblique angle (e.g., between 5° and 90° with respect to the central axis of the acceleration region **310**) with respect to a housing of the acceleration region **310** (e.g., the surrounding outer electrode **304**). In one example, the oblique angle may be 45° with respect to the central axis of the acceleration region **310**. In some embodiments, the eight ports may be configured at a single axial position along the central axis of the acceleration region **310** (that is, the eight ports may be equally spaced about a circumference or other perimeter of the acceleration region **310** at the axial position). In other embodiments, the ports may include multiple sets of eight ports, with each set of eight ports being equally spaced about a different axial position along the central axis of the acceleration region **310**. In an example embodiment, the sets of eight ports may be configured as interleaved pairs of sets, wherein a first set of eight ports may be positioned at a first axial location and a second set of eight ports may be positioned at a second, different axial location and rotated relative to the first set such that each port of the second set is positioned between a pair of ports of the first set with respect to the circumference of the acceleration region **310**. Specifically, in such an embodiment, each port of the first set of eight ports may be spaced around the circumference of the acceleration region **310** every 45°, and each port of the second set of eight ports may be spaced around the circumference of the acceleration region **310** every 45° offset (rotated) from the first set of ports by 22.5°, such that one port of the first and second sets is provided around the circumference of the acceleration region **310** every 22.5°. In additional or alternative embodiments, plasma injection may be performed azimuthally, e.g., along a chord perpendicular to the central axis of the acceleration region **310**, so as to generate an azimuthal flow within the acceleration region **310**. In some embodiments, additional gas-puff valves and/or plasma injectors may be included to allow for injection of more fuel gas (e.g., for longer lasting pinch discharges) and control of an axial pressure distribution of the fuel gas in the acceleration region **310** (e.g., for additional enhancement of the sheared ion velocity flow duration). In additional or alternative embodiments, the valves may be configured differently (e.g., asymmetrically distributed azimuthally and/or with different angular distributions) with other variations to achieve a substantially equivalent profile by compensating for effects of the variations.

[0063] In some embodiments, injecting the acceleration region **310** with pre-ionized gas may result in plasmas having a plasma temperature in a range of 1 to 10 eV. The plasma temperature may be decreased (e.g., by reducing an amount of energy input into a process gas used to generate the pre-ionized gas) so as to increase an electrical resistivity of the pre-ionized gas and resulting plasma. Specifically, increasing the electrical resistivity may decrease a tendency of the pre-ionized gas to oppose changes in magnetic flux and thereby a tendency to oppose motion within a magnetic field present in the acceleration region **310**.

[0064] As noted above, because an injection velocity of pre-ionized gas may be significantly greater than that of neutral gas, a velocity of the plasma within the acceleration region **310** may be up to 50×10^3 m/s. In some embodiments, injection of pre-ionized gas may provide flexibility in an amount of particles injected. Specifically, in an example embodiment, an amount of pre-ionized gas particles may be injected in 1/50 of a time utilized to inject the same amount of neutral gas particles. For example, an amount of time utilized to inject 10 Torr-L of neutral gas particles (where 1 Torr-L is proportional to 2.5×10^{19} molecules at 273 K) may be the same amount of time utilized to inject 500 Torr-L of pre-ionized gas particles. Similarly, in some embodiments, an injection rate (or mass flow rate) of pre-ionized gas may be varied according to power supply current and voltage (that is, a waveform of an injection pulse). As an example, increasing the power supply voltage (e.g., to between 100 V and 500 V) may concomitantly increase the injection velocity. As another example, increasing the power supply current (e.g., to between 1 A and 500 A) may concomitantly increase the injection rate. In some embodiments, the power supply voltage may be increased to between 750 V and 5 kV.

[0065] As discussed above, the gas-puff valves and/or plasma injectors may be activated either individually or in groups. An initial gas load inside the acceleration region **310** having desired axial and azimuthal profiles may be achieved by timing individual valves and/or groups of valves. Such valves (or groups thereof) may be timed in a fashion to align an arrival of the neutral and/or pre-ionized gas and/or mixtures thereof to a desired initial profile. Power supplies (e.g., power supplies **314** and **315** or separate, dedicated power supplies) may be timed to achieve ionization at a desired axial location and utilize the initial gas load to produce and sustain the sheared flow. In some embodiments, the power supplies may include a capacitor bank and a switch. In other embodiments, other suitable types of power supplies may be used, including flywheel power supplies.

[0066] Various combinations of (neutral gas) gas-puff valves with plasma injectors may be activated to achieve a desired level of power output. Moreover, plasma may be injected into the acceleration region **310** significantly (e.g., ~100×) faster than puffed neutral gas. A combination of such different injection speeds allowed by acceleration of plasma injection with neutral gas injection provides an even larger parameter space for optimization. Additionally, plasma injectors may serve to inject mass and precisely control locations of neutral gas ionization.

[0067] In an example embodiment, the first power supply **314** and the second power supply **315** may take the form of respective capacitor banks each capable of storing up to 10 MJ (e.g., 0.1 to 10 MJ). In one embodiment, the first power supply **314** and the second power supply **315** take the form of respective capacitor banks capable of storing up to 100-200 kJ and 3-4 MJ, respectively.

[0068] The plasma confinement system **300** may include the gas source **330** (e.g., a pressurized storage tank) and one or more first regulators **332** respectively configured to control gas flow from the gas source **330** through the one or more first valves **306**. Respective couplings (e.g., piping) between the one or more first regulators **332** and the one or more first valves **306** are omitted in FIG. **1** for clarity.

[0069] Similarly, the plasma confinement system **300** may include one or more second regulators **334** respectively configured to control gas flow from the gas source **330** through the one or more second valves **312**. Respective couplings (e.g., piping) between the one or more second regulators **334** and the one or more second valves **312** are omitted in FIG. **1** for clarity.

[0070] In some embodiments, the plasma confinement system **300** may include a first insulator **336** (e.g., having an annular cross section) between the inner electrode **302** and the outer electrode **304** to maintain electrical isolation between the inner electrode **302** and the outer electrode **304**. In other embodiments, such as when the inner electrode **302** is at least partially surrounded by the intermediate electrode **303**, the first insulator **336** may be positioned between the inner electrode **302** and the intermediate electrode **303** to maintain electrical isolation between the inner electrode **302** and the intermediate electrode **303**. In an example embodiment, the first insulator **336** may be formed from an electrically insulating material such as a glass, a ceramic, or a glass-ceramic material. In some embodiments, one or more valves (e.g., gas-puff valves and/or plasma injectors) may extend through or be provided in place of the first insulator **336** to inject neutral gas and/or pre-ionized gas at an end of the acceleration region **310** opposite to the first end **318** of the inner electrode **302**.

[0071] Similarly, the plasma confinement system **300** may include a second insulator **337** (e.g., having an annular cross section) between the intermediate electrode **303** and the outer electrode **304** to maintain electrical isolation between the intermediate electrode **303** and the outer electrode **304**. In an example embodiment, the second insulator **337** may be formed from an electrically insulating material such as a glass, a ceramic, or a glass-ceramic material.

[0072] The plasma confinement system **300** may include a vacuum chamber **338** that at least partially surrounds the inner electrode **302**, the intermediate electrode **303**, and/or the outer electrode **304**. In the example embodiment depicted in FIG. **1**, the vacuum chamber **338** entirely surrounds each of the inner electrode **302**, the intermediate electrode **303**, and the outer electrode **304** (and thereby the plasma confinement chamber **340**). In an example embodiment, the vacuum chamber **338** may be formed as a stainless steel pressure vessel. In some embodiments, a pressure inside the vacuum chamber **338** may range from 10^{-9} Torr to 20 Torr (e.g., 10^{-9} Torr to 10^{-3} Torr).

[0073] The plasma confinement system **300** may include a controller or other computing device **348**, which may include non-transitory memory on which executable instructions may be stored. The executable instructions may be executed by one or more processors of the controller **348** to perform various functionalities of the plasma confinement system **300**. Accordingly, the executable instructions may include various routines for operation, maintenance, and testing of the plasma confinement system **300**. The controller **348** may further include a user interface at which an operator of the plasma confinement system **300** may enter commands or otherwise modify operation of the plasma confinement system **300**. The user interface may include various components for facilitating operator use of the plasma confinement system **300** and for receiving operator inputs (e.g., requests to generate plasma arcs for thermonuclear fusion, etc.), such as one or more displays, input devices (e.g., keyboards, touchscreens, computer mice, depressible buttons, mechanical switches other mechanical actuators, etc.), lights, etc. The controller **348** may be communicably coupled to various components (e.g., valves, power supplies, etc.) of the plasma confinement system **300** to command actuation and use thereof (wired and/or wireless communication paths between the controller **348** and the various components are omitted from FIG. **1** for clarity).

[0074] Referring now to FIGS. **2**-**3**F, operational aspects of a plasma confinement system, such as the plasma confinement system **300** described in detail above with reference to FIG. **1**, are illustrated. Specifically, in FIG. **2**, a block diagram of a method **200** for operating the plasma confinement system is shown, and, in FIGS. **3**A-**3**F, schematic cross-sectional diagrams of a portion **350** of the plasma confinement system **300** of FIG. **1** and functionality thereof are respectively shown. Accordingly, FIGS. **1** and **3**A-**3**F, viewed together, illustrate at least some of the aspects of the method **200** as described below. In an example embodiment, operation of the plasma confinement system (e.g., the plasma confinement system **300**) may include initiating and driving a sheared ion velocity flow therein for stabilization of Z-pinch discharge.

[0075] In some embodiments, the method **200**, or a portion thereof, may be implemented as executable instructions stored in non-transitory memory of a computing device, such as a controller communicably coupled to the plasma confinement system. Moreover, in certain embodiments, additional or alternative sequences of steps may be implemented as executable instructions on such a computing device, where individual steps discussed with reference to the method **200** may be added, removed, substituted, modified or interchanged.

[0076] At block **902**, the method **200** may include directing gas, via one or more first valves, from within an inner electrode to an acceleration region of a plasma confinement chamber. In an example embodiment, the acceleration region may be located between the inner electrode and an outer electrode that substantially surrounds the inner electrode. In other embodiments, the acceleration region may be located between the inner electrode and an intermediate electrode that substantially surrounds the inner electrode, the outer electrode substantially surrounding the intermediate electrode.

[0077] For example, and as shown in FIGS. **3**A and **3**B, the one or more first valves **306** may direct a gas **912** from within the inner electrode **302** to the acceleration region **310** between the inner electrode **302** and the outer electrode **304** that substantially surrounds the inner electrode **302**. Specifically, FIG. **3**A illustrates an initial amount of the gas **912** entering the acceleration region **310** and FIG. **3**B illustrates an additional amount of the gas **912** entering the acceleration region **310**. As shown in FIG. **3**A, the acceleration region **310** may be included, along with the assembly region **326**, in the plasma confinement chamber **340**.

[0078] In some embodiments, directing the gas **912** via the one or more first valves **306** may include providing (e.g., via a power supply such as a capacitor bank that is not shown at FIGS. **3**A-**3**F) a first valve voltage to the one or more first valves **306** (e.g., to control terminals of the one or more first valves **306**) followed by providing a second valve voltage [e.g., via a DC power supply] to the one or more first valves **306**. In an example embodiment, the first valve voltage may be greater than the second valve voltage and the second valve voltage may be provided immediately (e.g., substantially immediately) after providing the first valve voltage.

[0079] At block **904**, the method **200** may include directing gas, via one or more second valves, from outside the outer electrode to the acceleration region.

[0080] For example, and as shown in FIGS. **3**A and **3**B, the one or more second valves **312** may direct a portion of the gas **912** into the acceleration region **310**.

[0081] In some embodiments, directing the gas **912** via the one or more second valves **312** may include providing (e.g., via a power supply such as a capacitor bank that is not shown) a third valve voltage to the one or more second valves **312** (e.g., to control terminals of the one or more second valves **312**) followed by providing a fourth valve voltage (e.g., via a DC power supply) to the one or more second valves **312**. In an example embodiment, the third valve voltage may be greater than the fourth valve voltage and the fourth valve voltage may be provided immediately (e.g., substantially immediately) after providing the third valve voltage.

[0082] After operation of the one or more first valves **306** and the one or more second valves **312**, a gas pressure at, e.g., directly adjacent to (upon release) or within (such as within a plenum of, when present), each of the one or more first valves **306** and the one or more second valves **312** may be up to 5800 Torr, such as within a range of 1000 to 5800 Torr (e.g., 5450 to 5550 Torr), prior to applying a voltage between the inner electrode **302** and the outer electrode **304** via the first power supply **314**. Correspondingly, after operation of the one or more first valves **306** and the one or more second valves **312**, a gas pressure within the acceleration region **310** may be up to 5800 Torr, such as within the range of 1000 to 5800 Torr (e.g., 5450 to 5550 Torr), prior to applying the voltage between the inner electrode **302** and the outer electrode **304** via the first power supply **314**. In an example embodiment, the gas pressure within the acceleration region **310** may decrease with increasing distance from a point of gas insertion and with passage of time after gas is no longer introduced to the acceleration region **310**.

[0083] At block **906**, the method **200** may include applying, via a first power supply, a voltage between the inner electrode and the outer electrode to convert at least a portion of the directed gas into a plasma having a substantially annular cross section, the plasma flowing axially within the acceleration region toward a first end of the inner electrode and a first end of the outer electrode.

[0084] For example, and as shown in FIGS. **3**C and **3**D, the first power supply **314** may apply the voltage between the inner electrode **302** and the outer electrode **304** to convert at least a portion of the gas **912** into a plasma **916** having a substantially annular cross section. The voltage applied by the first power supply **314** between the inner electrode **302** and the outer electrode **304** may result in a radial electric field within the acceleration region **310** up to 500 kV/m (e.g., within a range of 30 kV/m to 500 kV/m). Due to a magnetic field being generated by a current traveling through the plasma **916**, the plasma **916** may flow axially within the acceleration region **310** toward the first end **318** of the inner electrode **302** and the first end **322** of the outer electrode **304** (as shown in FIGS. **3**C and **3**D).

[0085] At block **908**, the method **200** may include applying, via a second power supply, a voltage between the inner electrode and the intermediate electrode to establish a plasma arc (e.g., a Z-pinch plasma) that flows between the intermediate electrode and the first end of the inner electrode. In an example embodiment, the intermediate electrode may be positioned at a first end of the outer electrode. In other embodiments, and as discussed above, the intermediate electrode may substantially surround the inner electrode, and the outer electrode may substantially surround the intermediate electrode.

[0086] For example, and as shown in FIGS. **3**E and **3**F, the second power supply (e.g., the second power supply **315** as described in detail above with reference to FIG. **1**; omitted in FIGS. **3**A-**3**F for clarity) may apply a voltage between the inner electrode **302** and the intermediate electrode **303** to confine the plasma **916** and establish a plasma arc **918** (also referred to herein as a Z-pinch plasma **918**) that flows between the intermediate electrode **303** and the first end **318** of the inner electrode **302**. As shown, the plasma arc **918** may be established when the plasma **916** moves beyond the acceleration region **310**. Specifically, the plasma arc **918** may flow into the assembly region **326** between the first end **318** of the inner electrode **302** and the intermediate electrode **303**. In some embodiments, such as when the inner electrode **302** functions as a cathode and the intermediate electrode **303** functions as an anode, each of a discharge current forming the plasma arc **918** and a sheared axial (ion velocity) flow stabilizing the discharge current may flow from the first end **318** of the inner electrode **302** to the intermediate electrode **303**. In other embodiments, such as when the inner electrode **302** functions as the anode and the intermediate electrode **303** functions as the cathode, the discharge current may flow from the intermediate electrode **303** to the first end **318** of the inner electrode **302** and the sheared axial flow may flow from the first end **318** of the inner electrode **302** to the intermediate electrode **303**. In some embodiments, to augment the sheared flow profile created by neutral gas injection, injection of pre-ionized gas using plasma injectors, plasma guns, or ion sources may be employed in conjunction. In such embodiments, accordingly, plasma injection may occur rapidly and on the same scale as blocks **902** and **904**, and may be used to control formation/initialization and dynamics of the plasma arc **918**.

[0087] In an example embodiment, the plasma arc **918** may exhibit the sheared axial flow and have a radius up to 5 mm (e.g., between 0.05 and 5 mm), an ion temperature up to 100000 eV, such as between 900 and 30000 eV (e.g., 900 to 2000 eV), an electron temperature greater than 500 eV, an ion number density greater than 1×10^{23} ions/m^3 and/or an electron number density greater than 1×10^{23} electrons/m^3, and/or a magnetic field over 8 T, and/or may be stable for at least 1 μs, such as between 5 and 10 us or up to 1 ms. It should be noted that such ranges are exemplary and may be modified based on an operating mode of the plasma confinement system **300** or based on modifications to a size, function, configuration, etc. of the plasma confinement system **300**. For example, if the size of the plasma confinement system **300** increases, such ranges may scale proportionally (e.g., linearly, exponentially, etc.).

[0088] It should be noted that blocks **906** and **908** may be implemented by other means of controlling (a) the voltage between the inner electrode **302** and the outer electrode **304** and (b) the voltage between the inner electrode **302** and the intermediate electrode **303**, as one of skill in the art will recognize. For example, a power supply may provide a voltage between the intermediate electrode **303** and the outer electrode **304**, instead of between the inner electrode **302** and the intermediate electrode **303**.

[0089] Referring now to FIG. **4**, a schematic cross-sectional diagram of a plasma confinement system **900**, such as may be included within a thermonuclear fusion reactor, is shown. The plasma confinement system **900** may generate a plasma arc within an assembly region **630** of a plasma confinement chamber **610**, the plasma arc confined, compressed, and sustained by an axially symmetric magnetic field. The axially symmetric magnetic field may be stabilized by a sheared ion velocity flow driven by electrical discharge between a pair of electrodes interfacing with the plasma confinement chamber **610**.

[0090] The plasma confinement system **900** may be assembled and configured similarly to the plasma confinement system **300** and may operate in a substantially similar manner in practice. The primary differences between the plasma confinement system **300** as depicted in FIG. **1** and the plasma confinement system **900** as depicted in FIG. **4** include relative positioning and spatial configuration of the intermediate electrode **303** (in FIG. **1**) and relative positioning and spatial configuration of an intermediate electrode **920** (in FIG. **4**), which will be discussed in greater detail below. Excepting certain assembly and operational aspects which may arise from such differences, the description provided above with reference to FIGS. **1**-**3**F may be additionally applied to the embodiment depicted in FIG. **4**. In certain embodiments, additional subsystems and/or functionalities may also be included in the plasma confinement system **900** which were not described in detail above with reference to FIGS. **1**-**3**F and which may be additionally applied to the embodiments depicted in FIGS. **1**-**3**F.

[0091] As such, in one embodiment, at least one of the pair of electrodes driving the sheared ion velocity flow is a static, solid electrode including an electrode material which supplements or increases thermonuclear fusion within the plasma confinement chamber **610** during generation of the plasma arc. In an additional or alternative embodiment, at least one of the pair of electrodes may be an in situ renewable electrode including a protective film of a flowing, liquid metal which may ablate from an external surface of the electrode upon interaction with the plasma arc and thereby mitigate high-discharge erosion of the external surface.

[0092] A set of Cartesian coordinate axes **452** is shown in FIG. **4** for contextualizing positions of the various components of the plasma confinement system **900**. Specifically, x-, y-, and z-axes are provided which are mutually perpendicular to one another, where the x- and y-axes define a plane of the schematic cross-sectional diagram shown in FIG. **4** and the z-axis is perpendicular thereto. In some embodiments, a direction of gravity may be parallel to and coincident with any direction in the plane of the schematic cross-sectional diagram of FIG. **4**. For example, the direction of gravity may be parallel and coincident with a positive direction of the x-axis. In additional or alternative embodiments, the direction of gravity may be within a plane defined by the y- and z-axes (e.g., parallel and coincident with a negative direction of the y-axis).

[0093] In an example embodiment, the plasma confinement system **900** may include an outer electrode **650** separated physically and functionally from an external vacuum boundary **910**, the external vacuum boundary **910**, together with portions of an inner electrode **660**, forming a vacuum vessel **640** as a low pressure container including the plasma confinement chamber **610**. The intermediate electrode **920** may be positioned so as to have a radius in between a radius of the inner electrode **660** and a radius of the outer electrode **650**. Specifically, the intermediate electrode **920** may substantially surround the inner electrode **660** and the outer electrode **650** may substantially surround the intermediate electrode **920**. For example, the inner electrode **660** may include one end **665** that is at least partially surrounded by the intermediate electrode **920** and the intermediate electrode **920** may include one end **965** that is at least partially surrounded by the outer electrode **650**.

[0094] The plasma confinement system **900** may incorporate at least two functionally separate power supplies, e.g., at least one primary power supply **930** primarily arranged and controlled to drive a Z-pinch (discharge) current **950** (I_{pinch}), and at least one additional power supply **940** primarily arranged and controlled to drive a residual current **867**. In some embodiments, the at least one primary power supply **930** may be separate power supply device(s) from the at least one additional power supply **940**. In other embodiments, the at least one primary power supply **930** and the at least one additional power supply **940** may be components of the same power supply device.

[0095] For example, in at least one embodiment, a single power supply device may have a plurality of outputs which individually provide an amount of power to enable performance of a respective function (e.g., drive the Z-pinch current **950**, drive the residual current **867**, etc.). Such an arrangement may be based on at least two power supplies (e.g., one primary power supply **930** and one additional power supply **940**) and may allow for additional control of the Z-pinch current **950** and sheared flow stabilization thereof. In principle, the at least two power supplies may be scaled, charged, and controlled such that the Z-pinch current **950** and the stabilization thereof may be maintained for commensurate time periods before any of the at least two power supplies prematurely runs short or out of stored energy.

[0096] In certain embodiments, the plasma confinement system **900** may incorporate a "tapered electrodes" configuration, characterized by broadening a gap between the inner electrode **660** and the intermediate electrode **920** by tapering, along the x-axis, the end **965** of the intermediate electrode **920** outwards to increase a volume of at least a portion of the acceleration region **620**, e.g., in a direction of the (unsupported) ends **665** and **965**. In one example, the taper may be between 0 and 15 degrees from a central axis of the plasma confinement system **900** (e.g., parallel to the x-axis). Such an arrangement may facilitate a transfer of momentum from plasma heated by the residual current **867** to neutral gas, e.g., along a positive direction of the x-axis, thereby creating and sustaining sheared flow stabilization. The momentum transfer may be described and modeled using methodology applicable to design/optimization of "de Laval nozzles" as known in the field of jet propulsion.

[0097] While techniques described herein are discussed in connection with thermonuclear fusion and, for example, harnessing energy production therefrom, the techniques described herein can be used for other purposes, such as heat generation (e.g., for manufacturing utilizing relatively high temperatures) and propulsion. For example, the plasma confinement system **300** of FIG. **1** or the plasma confinement system **900** of FIG. **4** may be modified at least by removing the vacuum chamber **338** or the external vacuum boundary **910**, respectively, and introducing an opening in one end of the outer electrode **650** to allow fusion products to escape (e.g., parallel to the x-axis). In one embodiment, a magnetic nozzle (not shown at FIG. **4**) is positioned downstream of the outer electrode **650**, e.g., to the right of the outer electrode **650** with respect to the x-axis, to collimate the plasma to reduce any exhaust plume divergence.

[0098] The plasma confinement system **900** may include a controller or other computing device **948**, which may include non-transitory memory on which executable instructions may be stored. The executable instructions may be executed by one or more processors of the controller **948** to perform various functionalities of the plasma confinement system **900**. Accordingly, the executable instructions may include various routines for operation, maintenance, and testing of the plasma confinement system **900**. The controller **948** may further include a user interface at which an operator of the plasma confinement system **900** may enter commands or otherwise modify operation of the plasma confinement system **900**. The user interface may include various components for facilitating operator use of the plasma confinement system **900** and for receiving operator inputs (e.g., requests to generate plasma arcs for thermonuclear fusion, etc.), such as one or more displays, input devices (e.g., keyboards, touchscreens, computer mice, depressible buttons, mechanical switches or other mechanical actuators, etc.), lights, etc. The controller **948** may be communicably coupled to various components (e.g., valves, power supplies, etc.) of the plasma confinement system **900** to command actuation and use thereof (wired and/or wireless communication paths between the controller **948** and the various components are omitted from FIG. **4** for clarity).

[0099] Referring now to FIG. **5**, a block diagram of a method **400** for operating a plasma confinement system, such as any of the plasma confinement systems described in detail above with reference to FIGS. **1-4**, and forming an electrode therefor, where the electrode may be formed with an electrode material which supplements or increases thermonuclear fusion during the operation of the plasma confinement system, is shown. In an example embodiment, the electrode material may be a metal hydride, such as a deuteride and/or a tritide including one or more of Ti, Zr, Sc, Mg, V, or ^{6}Li (e.g., TiD_2, ^6LiD, etc.), or any alloy formed by any combination of one or more of the preceding metals. The metal hydride may decompose to provide hydronic fuel gas (e.g., H_2, D_2, T_2) when exposed to operational temperatures of the plasma confinement system (e.g., during application of a Z-pinch discharge current to generate a plasma arc), and may supply free neutrons upon ionic bombardment (e.g., with deuterium and/or tritium) and/or free tritium atoms upon neutronic bombardment.

[0100] In some embodiments, the method **400**, or a portion thereof, may be implemented as executable instructions stored in non-transitory memory of a computing device, such as a controller communicably coupled to the plasma confinement system. Moreover, in certain embodiments, additional or alternative sequences of steps may be implemented as executable instructions on such a computing device, where individual steps discussed with reference to the method **400** may be added, removed, substituted, modified or interchanged.

[0101] At block **402**, the method **400** may include evaporating a metal precursor layer onto a bulk material. In some embodiments, the bulk material may include a metal, such as copper (Cu), tungsten (W), or Ti. In additional or alternative embodiments, the metal precursor layer may include one or more of Ti, Zr, Sc, Mg, V, ^{6}Li, or any alloy formed by any combination of one or more of the preceding metals. The metal precursor layer may be formed to be less than, or within a threshold range of, a predetermined thickness. In an example embodiment, the predetermined thickness may be a millimeter (e.g., on an order of hundreds of microns).

[0102] In an example embodiment, the bulk material may form a shaft (e.g., a substantially cylindrical body) ending in a nosecone. In one example, the metal precursor layer may be evaporated on only the nosecone. To confine the metal precursor layer to cover only a portion (e.g., the nosecone) of the bulk material, the bulk material may be masked so that the metal precursor layer may be evaporated on only an exposed, unmasked portion (e.g., the nosecone) of the bulk material.

[0103] At block **404**, the method **400** may include loading the metal precursor layer with deuterium and/or tritium generated via an ion beam source to form an electrode for the plasma confinement system. In an example embodiment, the ion beam source may be external to and separate from the plasma confinement system. Though in other embodiments the metal precursor layer may be loaded during operation of the plasma confinement system (e.g., via the plasma arc generated by application of the Z-pinch discharge current) and thus the loading may additionally or alternatively occur following block **406** (see below), the external ion beam source may load the deuterium and/or tritium at an appreciably faster rate. For example, the external ion beam source may be a 10 to 100 kV deuterium ion source which may optionally load tritium ions as well. In other examples, the tritium ions may be loaded via an additional external ion beam source. Example ion implantation depths in Ti (which may, in some examples, form the metal precursor layer) are provided in FIG. **6** for H, D, T, ^{3}He, and ^{4}He ions.

[0104] In an example embodiment, upon loading of the metal precursor layer with deuterium and/or tritium, an electrode material layer (e.g., a metal layer loaded with deuterium and/or tritium) may be formed on the bulk material. The electrode material layer may include a metal hydride having the formula of MH_n (e.g., a metal deuteride having the formula of MD_n and/or a metal tritide having the formula of MT_n), where n is a molar ratio of hydrogen atoms (e.g., any one of various hydrons, including D and/or T) to metal ions M in the solid phase. For example, n may be 2, such as in TiH_2 (e.g., TiD_2 and/or TiT_2). Continuing with the example of TiH_2, for a given mass of Ti m_{Ti} in the electrode material layer, a number of Ti atoms N_{Ti} may be given as:

$$N_{Ti} = m_{Ti}\frac{6.02\times 10^{23}\ \mathrm{mol}^{-1}}{48\ \mathrm{g}\cdot\mathrm{mol}^{-1}} \tag{4}$$

where the Avogadro constant is approximated as 6.02×10^{23} mol^{-1} and the atomic mass of Ti is approximated at 48 $\mathrm{g}\cdot\mathrm{mol}^{-1}$. Applying equation (4) to TiH_2 including $m_{Ti}=1$ g, $N_{Ti}\cong1.25\times10^{22}$ and a number of H atoms is $2N_{Ti}\cong2.5\times10^{22}$.

[0105] At block **406**, the method **400** may include positioning the electrode so as to be exposed to a plasma confinement chamber of the plasma confinement system. In an example embodiment, the plasma confinement chamber may be partitioned into an acceleration region and an assembly region, wherein the electrode may be positioned so as to be exposed to each of the acceleration region and the assembly region. As an example, the electrode may be an inner electrode coaxial with the plasma confinement chamber so as to extend through the acceleration region such that an end of the inner electrode may be exposed to the assembly region. As an additional or alternative example, the electrode may be an outer electrode at least partially circumferentially surrounding the inner electrode and at least partially defining an outer boundary of each of the acceleration region and the assembly region. As another example, the electrode may be an intermediate electrode at least partially circumferentially surrounding the inner electrode and at least partially defining an outer boundary of the acceleration region, extending such that an end of the intermediate electrode may be exposed to the assembly region.

[0106] At block **408**, the method **400** may include generating a request to initialize the plasma confinement system, according to which an initialization phase of the plasma confinement system may be initiated. In an example embodiment, the request may be generated responsive to receiving a user input, e.g., from an operator of the plasma confinement system. For instance, initialization of the plasma confinement system may be triggered or otherwise initiated via an operator interacting with a user interface, e.g., a push button switch, toggle switch, or other mechanical actuator, a keyboard, a touchscreen, a cursor input, etc.

[0107] At block **410**, the method **400** may include initiating a plasma arc generation phase of the plasma confinement system, e.g., following the initialization phase. Specifically, in an example embodiment, the plasma arc generation phase may be initiated at least by powering up the plasma confinement system (e.g., one or more power supplies may supply power to various components utilized during the plasma arc generation phase) and providing fuel gas for forming a plasma to the plasma confinement chamber by increasing one or more valve openings. In an example embodiment, the fuel gas may include one or more of D_2 or T_2.

[0108] At block **412**, the method **400** may include generating the plasma arc in the plasma confinement chamber, e.g., during the plasma arc generation phase. In an example embodiment, the Z-pinch discharge current may be applied at a repetition rate between the electrode including the electrode material layer and another electrode to generate the plasma arc. Accordingly, during operation of the plasma confinement system, the electrode may function as either a cathode in some embodiments or an anode in other embodiments. The Z-pinch discharge current may be stabilized by a sheared ion velocity flow created and maintained via an applied residual current. As a result of the plasma arc generation, the electrode may be heated and/or the electrode may be bombarded with deuterium, tritium, and free neutrons (e.g., resulting from thermonuclear fusion within the plasma arc). An amount of heat generated at the electrode and/or ionic/neutronic bombardment may depend on a position of the electrode in relation to the plasma arc (e.g., whether or not the plasma arc is directly interacting with the electrode).

[0109] In an example embodiment, the metal hydride included in the electrode material layer may decompose to a metal and the fuel gas (e.g., via equation (2)) when the electrode is heated to a decomposition temperature during operation of the plasma confinement system to generate the plasma arc. Example isothermal pressures for decomposition of various TiH_n species are provided in FIG. **7**.

[0110] In an additional or alternative embodiment, the metal hydride included in the electrode material layer may release or expel free neutrons upon ionic bombardment of the metal hydride. Specifically, the deuterium and/or tritium from the plasma arc may interact with hydrons in the metal hydride via a thermonuclear fusion reaction (e.g., reaction (1)) to generate ^4He and free neutrons.

[0111] In an additional or alternative embodiment wherein the metal hydride includes ^6Li, the metal hydride included in the electrode material layer may release or expel free tritium atoms upon neutronic bombardment of the metal hydride. Specifically, free neutrons from the plasma arc may interact with ^6Li in the metal hydride (e.g., via reaction (3)) to generate tritium, as well as deuterium and ^4He.

[0112] In certain embodiments, the metal hydride may be replenished after depletion thereof following a duration of use of the plasma confinement system. For example, the duration of use may be 1000 hours.

[0113] Referring now to FIG. **6**, a plot **500** of ion implantation depth in Ti as a function of ion energy is shown for various example ions. The Ti may be included, for example, in a bulk material or in a relatively thin layer or film disposed on a bulk material. In the plot **500**, an abscissa indicates the ion energy (in keV) and an ordinate indicates the ion implantation depth (in μm). The ion implantation depths for H, D, T, ^3He, and ^4He ions in Ti are plotted in curves **502**, **504**, **506**, **508**, and **510**, respectively. As shown, for a given ion energy plotted in the plot **500**, the ion implantation depth may increase according to a sequential order of ^3He, ^4He, H, D, and T. Accordingly, for a given ion implantation depth, higher energy ion beams may be utilized to implant D and T in Ti as compared to ion beams utilized for H, ^3He, and ^4He.

[0114] Referring now to FIG. **7**, a plot **600** of isothermal pressure as a function of H:Ti atomic ratio n is shown for various example titanium hydrides (TiH_n). In the plot **600**, an abscissa indicates the H:Ti atomic ratio on a linear scale and an ordinate indicates the isothermal pressure (in Torr) on a logarithmic scale. The isothermal pressure values are plotted for steady-state decomposition of TiH_n at various fixed temperatures, including 200° C. (points **602**), 225° C. (points **604**), 250° C. (points **606**), 275° C. (points **608**), and 300° C. (points **610**). As shown, for a given H:Ti atomic ratio in the plot **600**, the isothermal pressure may increase with increasing temperature. Moreover, for a given temperature, the isothermal pressure may trend upwards with increasing H:Ti atomic ratio. Accordingly, higher temperatures and higher H:Ti atomic ratios may generate higher pressures as a result of decomposition of TiH_n to Ti and H_2.

[0115] Referring now to FIGS. **8**A and **8**B, schematic cross-sectional diagrams of an electrode **702** (also referred to herein as an electrode body **702** or an in situ renewable electrode **702**) in a plasma confinement chamber **706** of a plasma confinement system **700** for a thermonuclear fusion reactor **701** are respectively shown. Specifically, the schematic cross-sectional diagram of FIG. **8**A depicts the electrode **702** and the plasma confinement chamber **706** during operation of the thermonuclear fusion reactor **701** and the schematic cross-sectional diagram of FIG. **8**B depicts the electrode **702** and the plasma confinement chamber **706** prior to and following operation of the thermonuclear fusion reactor **701**. During operation of the thermonuclear fusion reactor **701**, a plasma arc **708** may be generated and subsequently confined, compressed, and sustained by an axially symmetric magnetic field. The axially symmetric magnetic field may be stabilized by a sheared ion velocity flow driven by electrical discharge between the electrode **702** and at least one additional electrode interfacing with the plasma confinement chamber **706**.

[0116] The electrode **702** may be referred to as an in situ renewable electrode **702** in that the electrode **702** may include a protective film **736** (also referred to herein as a meniscus **736**) of a liquid metal **718** which may flow continuously (e.g., without interruption or with no appreciable delay) and ablate from an external surface **704*a*** of the electrode **702** upon interaction with the plasma arc **708** generated during operation of the thermonuclear fusion reactor **701**. As a portion of the electrode **702** interacting with the plasma arc **708** may be continuously replenished with the flowing, liquid metal **718**, erosion of the external surface **704*a*** (and thereby of the electrode **702** as a whole) during operation of the thermonuclear fusion reactor **701** may be mitigated or altogether obviated.

[0117] Though the electrode **702** is described below in the context of the plasma confinement chamber **706**, the electrode **702** may be positioned in any of the plasma confinement systems described hereinabove as a replacement for an electrode therein. As an example, the electrode **702** may replace the inner electrode **302** included in the plasma confinement system **300** described in detail above with reference to FIGS. **1** and **3**A-**3**F. As another example, the electrode **702** may replace the inner electrode **660** of the plasma confinement system **900** described in detail above with reference to FIG. **4**. Moreover, only a portion of the plasma confinement system **700** (and thereby the thermonuclear fusion reactor **701**) is shown in FIGS. **8**A and **8**B and other components (e.g., additional electrodes, power supplies, insulators, etc.) may be added, removed, substituted, modified or interchanged, such as one or more components from the plasma confinement system **300** and/or the plasma confinement system **900**.

[0118] A set of Cartesian coordinate axes **752** is shown in FIGS. **8**A and **8**B for contextualizing positions of the various components of the thermonuclear fusion reactor **701** and for comparing between the schematic cross-sectional diagrams of FIGS. **8**A and **8**B. Specifically, x-, y-, and z-axes are provided which are mutually perpendicular to one another, where the x- and y-axes define a plane of each of the schematic cross-sectional diagrams of FIGS. **8**A and **8**B and the z-axis is perpendicular thereto. In some embodiments, a direction of gravity may be parallel to and coincident with any direction in the plane of the schematic cross-sectional diagrams of FIGS. **8**A and **8**B. In one example, and as discussed in examples described hereinbelow, the direction of gravity may be parallel and coincident with a positive direction of the x-axis. In additional or alternative embodiments, the direction of gravity may be within a plane defined by the y- and z-axes (e.g., parallel and coincident with a negative direction of the y-axis).

[0119] In an example embodiment, the electrode **702** may be formed in a substantially cylindrical shape having with a tapered, rounded base or nosecone **704**. Additionally or alternatively, the electrode **702** may be elongated along the x-axis, such that a length of the electrode **702** along the x-axis is longer than a length of the electrode **702** along the y- and z-axes.

[0120] In an example embodiment, the electrode **702** may be formed from a relatively high purity material, e.g., so as to preclude formation of (unexpected) activation products during neutronic bombardment. Additionally or alternatively, the electrode **702** (e.g., the nosecone **704** thereof) may be cast or additively manufactured from a material selected for relatively high resistance to neutron damage, such as silicon carbide. In some embodiments, the electrode **702** may include one or more of a metal (e.g., Cu and/or W), graphite, or a semiconductor (e.g., silicon carbide).

[0121] In some embodiments, the electrode **702** may be formed as a unitary component inclusive of the nosecone **704**. In other embodiments, the nosecone **704** may be removably fastened or fixedly adhered to another portion/surface of the electrode **702**. Accordingly, in some examples, one or more fasteners or other locking structures may be provided to removably fix the nosecone **704** in position. In other examples, the nosecone **704** may be welded or otherwise adhered (e.g., with an adhesive) in position. In additional or alternative embodiments, the nosecone **704** may be electrically coupled to another portion/surface of the electrode **702** via electrical lines/wires or by forming components of the electrode **702** (including the nosecone **704**) from one or more electrically conductive materials which transfer electrical current between the components when the components are placed in physical contact with one another.

[0122] The electrode **702** may be at least partially enclosed or otherwise contained within the plasma confinement chamber **706**. For example, a majority of the electrode **702** may be circumferentially surrounded by the plasma confinement chamber **706** with one end of the electrode **702** (not shown in FIGS. **8**A and **8**B) extending from the plasma confinement chamber **706** in a negative direction of the x-axis and/or forming one wall of the plasma confinement chamber **706**.

[0123] During operation of the thermonuclear fusion reactor **701**, the plasma arc **708** may be generated by applying a discharge current between the electrode **702** and at least one additional electrode (not shown at FIGS. **8**A and **8**B). As a result of the axially symmetric magnetic field generated by the discharge current, the plasma arc **708** may be confined and compressed so as to flow toward the electrode **702** along a central axis **710** (e.g., parallel to the x-axis, the plasma arc **708** flowing in the negative direction thereof), as indicated by arrows **712**.

[0124] The electrode **702** may be positioned such that a central axis of the substantially cylindrical shape is coincident with the central axis **710** of the plasma arc **708**. Accordingly, the external surface **704***a* of the electrode **702**, more specifically, at the nosecone **704**, may intersect with the central axis **710** of the plasma arc **708** during generation and confinement thereof. As such, the plasma confinement chamber **706** may entirely surround an exterior of the nosecone **704**.

[0125] The electrode **702** may include an internal reservoir **714** enclosed or otherwise contained therein. In an example embodiment, the internal reservoir **714** may occupy a core region of the electrode **702**, e.g., extending along the central axis thereof and radially symmetric thereabout. As described below, the electrode **702** may include a plurality of channels including a first portion for flowing the liquid metal **718** to the internal reservoir **714**, a second portion for flowing an inert gas **726** to the internal reservoir **714**, a third portion for flowing the liquid metal **718** from the internal reservoir **714** to the exterior of the nosecone **704**, and a fourth portion for flowing a heat exchange fluid **741** to maintain or adjust (e.g., increase or decrease, depending upon an operational mode or one or more conditions of the plasma confinement system **700**) a temperature of the electrode **702** and/or a temperature of the liquid metal **718**.

[0126] The internal reservoir **714** may contain at least a portion of the liquid metal **718**, the liquid metal **718** fed to the internal reservoir **714** via a liquid metal supply channel **716** (e.g., formed as a conduit or a pipe) as indicated by an arrow **734***a*. Specifically, the liquid metal supply channel **716** may fluidly couple the internal reservoir **714** to a liquid metal source **720** (e.g., a pressurized storage tank), the liquid metal source **720** positioned external to the plasma confinement chamber **706**. The liquid metal source **720** may contain at least a portion of the liquid metal **718** which may be controllably fed to the internal reservoir **714** (see the arrow **734***a*) via actuation of a valve **722** (e.g., controlled by a corresponding regulator; not shown at FIGS. **8**A and **8**B). The valve **722** is shown in FIG. **8**A in an open position to allow the liquid metal **718** to substantially freely flow to the internal reservoir **714**, though the valve **722** may also be placed in a closed position (see FIG. **8**B) to prevent the liquid metal **718** from flowing from the liquid metal source **720** to the internal reservoir **714**. In some embodiments, the valve **722** may be continuously variable, such that the valve **722** may take on a range of partially open positions which permit greater flow than the closed position and less flow than the open position.

[0127] In an example embodiment, the liquid metal **718** may include any metal which may be present in a liquid state under operating temperatures of the thermonuclear fusion reactor **701**. Additionally or alternatively, the liquid metal **718** may be selected for relatively high resistance to neutron damage (in certain embodiments, the liquid metal **718** may be more resistant to neutron damage than a composition of the electrode **702**). Moreover, radiative losses may scale with quantity and atomic number of contaminants. Accordingly, the liquid metal **718** may include lithium (Li), for example. In additional or alternative examples, an additive may be included, e.g., to modify viscosity, surface tension, etc. In certain examples, the additive may be selected for reduced toxicity and flammability. As one example, the liquid metal **718** may include bismuth (Bi) and/or lead (Pb), e.g., in the form of a Li compound/composite/alloy including Bi and/or Pb. In other embodiments, liquid lithium hydride may supplant some or all of the liquid metal **718** for similar purposes, e.g., for forming the protective film **736** on the external surface **704***a*.

[0128] The internal reservoir **714** may further contain at least a portion of the inert gas **726**, the inert gas **726** fed to the internal reservoir **714** via an inert gas supply channel **724** (e.g., formed as a conduit or a pipe). Specifically, the inert gas supply channel **724** may fluidly couple the internal reservoir **714** to an inert gas source **728** (e.g., a pressurized storage tank), the inert gas source **728** positioned external to the plasma confinement chamber **706**. The inert gas **726** is depicted as arrows in FIG. **8**A, the arrows directed in a flow direction of the inert gas **726** when the inert gas **726** is being supplied to the internal reservoir **714** during operation of the thermonuclear fusion reactor **701**. The inert gas source **728** may contain any remaining portion of the inert gas **726** (e.g., any remaining inert gas **726** excepting the portion contained within the inert gas source **728**), which may be controllably fed to the internal reservoir **714** via actuation of a valve **730** (e.g., controlled by a corresponding regulator; not shown at FIGS. **8**A and **8**B). The valve **730** is shown in FIG. **8**A in an open position to allow the inert gas **726** to substantially freely flow to the internal reservoir **714**, though the valve **730** may also be placed in a closed position (see FIG. **8**B) to prevent the inert gas **726** from flowing from the inert gas source **728** to the internal reservoir **714**. In some embodiments, the valve **730** may be continuously variable, such that the valve **730** may take on a range of partially open positions which permit greater flow than the closed position and less flow than the open position.

[0129] In an example embodiment, the inert gas **726** may include any gas which does not appreciably react with or otherwise degrade the liquid metal **718** and the electrode **702**. For example, the inert gas **726** may include helium (He). In additional or alternative examples, the inert gas **726** may include one or more noble gases [neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), radon (Rn), etc.].

[0130] During operation of the thermonuclear fusion reactor **701**, the liquid metal **718** in the internal reservoir **714** may be maintained at, above, or within a threshold range of a liquid metal level **754**, the liquid metal level **754** preselected to maintain a liquid metal flow rate for formation and sustainment of the protective film **736**. Accordingly, in some embodiments, the liquid metal level **754** may be adjusted so as to maintain the liquid metal flow rate. Additionally or alternatively, the liquid metal level **754** may be adjusted responsive to a liquid metal level **758** corresponding to an amount of the liquid metal **718** remaining in the liquid metal source **720** (e.g., the liquid metal level **754** may be progressively decreased responsive to the liquid metal level **758** progressively decreasing). Sensors positioned within the internal reservoir **714** and the liquid metal source **720** (not shown at FIGS. **8**A and **8**B) may monitor the liquid metal levels **754** and **758**, respectively.

[0131] The electrode **702** may include a plurality of internal liquid flow channels **732** fluidly coupling the internal reservoir **714** to the exterior of the nosecone **704**. Each of the plurality of internal liquid flow channels **732** may include: a main liquid flow channel **732***a* fluidly coupled to and extending from the internal reservoir **714**, and a plurality of liquid flow capillaries **732***b* which fluidly couple the main liquid flow channel **732***a* to the exterior of the nosecone **704**.

[0132] In an example embodiment, the central axis of the electrode **702** may be coaxial with the direction of gravity, the direction of gravity being coincident with the positive direction of the x-axis. Accordingly, the nosecone **704** may be positioned below the internal reservoir **714** with respect to the direction of gravity. Moreover, upon extending from the internal reservoir **714**, each of the plurality of internal liquid flow channels **732** (e.g., the main liquid flow channel **732***a* thereof) may be initially oriented upwards and opposite the nosecone **704**. After orienting upwards, each of the plurality of internal liquid flow channels **732** (e.g., the main liquid flow channel **732***a* thereof) may arch downwards and towards the nosecone **704**. As such, a combined force from an amount of the liquid metal **718** supplied to the internal reservoir **714** (corresponding to the liquid metal level **754**) and the inert gas pressure within the internal reservoir **714** may overcome gravitational force to flow the liquid metal **718** through the initially upward orientation of the plurality of internal liquid flow channels **732**, after which gravitational force may assist in increasing the liquid metal flow rate.

[0133] At least a portion of the liquid metal **718** may be fed from the internal reservoir **714** and along the plurality of internal liquid flow channels **732** to the external surface **704***a*. Specifically, for each of the plurality of internal liquid flow channels **732**, the liquid metal **718** may flow along the main liquid flow channel **732***a*, as indicated by arrows **734***b*, to the plurality of liquid flow capillaries **732***b* and along the plurality of liquid flow capillaries to the external surface **704***a*, as indicated by arrows **734***c*. Though the plurality of liquid flow capillaries **732***b* are depicted in FIGS. **8**A and **8**B as being fluidly coupled to the external surface **704***a* at the nosecone **704** and on either side of the central axis **710** of the plasma arc **708** with respect to the y-axis, in other embodiments, at least a portion of the plurality of liquid flow capillaries **732***b* may be fluidly coupled to the external surface **704***a* at the nosecone **704** so as to intersect with the central axis **710** and/or at least a portion of the plurality of liquid flow capillaries **732***b* may be fluidly coupled to other portions of the external surface **704***a* apart from the nosecone **704** altogether.

[0134] Upon flowing to the external surface **704***a*, at least a portion of the liquid metal **718** may form the protective film **736** between the external surface **704***a* and the exterior of the nosecone **704**. The protective film **736** may be retained (e.g., anchored, adhered, or otherwise retained) on the external surface **704***a* at least via capillary action induced by the plurality of liquid flow capillaries **732***b*. The protective film **736**, being retained on the nosecone **704** and substantially symmetric about the central axis of the electrode **702**, may be positioned so as to directly interact with the plasma arc **708** during operation of the thermonuclear fusion reactor **701** (that is, the protective film **736** may be positioned such that the plasma arc **708** physically interacts with the protective film **736** absent any intervening components or volumes).

[0135] As such, a portion of the liquid metal **718** may be fed (e.g., from the liquid metal source **720**) to the internal reservoir **714** and along the plurality of internal liquid flow channels **732** to the external surface **704***a*. A remaining portion of the liquid metal **718** (e.g., any remaining liquid metal **718** excepting the portion contained within the electrode body **702** and being fed to the external surface **704***a*) may form the protective film **736** on the external surface **704***a*.

[0136] During operation of the thermonuclear fusion reactor **701**, portions of the protective film **736** may ablate from the external surface **704***a* at a liquid metal ablation rate via interaction with the plasma arc **708** and the high discharge current sustaining the plasma arc **708**. The portions of the protective film **736** ablating from the external surface **704***a* may be continuously (e.g., without interruption or with no appreciable delay) replenished by the liquid metal **718**

flowing to the external surface **704***a* from the internal reservoir **714** at the liquid metal flow rate.

[0137] In embodiments wherein the direction of gravity is not parallel to the positive direction of the x-axis, the protective film **736** may extend at least partially down the external surface **704***a* and below the nosecone **704** along a negative direction of the x-axis. In such embodiments, various structures may be provided on the electrode **702** or within the plasma confinement system **700** so that the flowing liquid metal **718** may not interfere with operation of the plasma confinement system **700**. For example, ports/openings along the external surface **704***a* (e.g., for one or more fuel gas supply channels **742**) may extend from the external surface **704***a* parallel to a plane defined by the y- and z-axes and/or a drain/trough may be provided at a base of the electrode **702** opposite to the nosecone **704** with respect to the x-axis to collect excess liquid metal **718**. In additional or alternative embodiments wherein the direction of gravity is not parallel to the positive direction of the x-axis, the protective film **736** may be asymmetric about the central axis **710** of the plasma arc **708**. However, in any of the preceding embodiments, the protective film **736** may still intersect with the central axis **710** of the plasma arc **708** during operation of the plasma confinement system **700** so as to be positioned between the plasma arc **708** and the external surface **704***a*.

[0138] The electrode **702** may include one or more heat exchange fluid flow channels **740** containing the heat exchange fluid **741**. In an example embodiment, the heat exchange fluid **741** may maintain a temperature of the liquid metal **718** (e.g., of the protective film **736** formed a portion of the liquid metal **718**) and/or a portion or substantially an entirety of the electrode **702**. In some embodiments, a plurality of heat exchange fluid flow channels **740** may be included in the electrode **702**, e.g., with each heat exchange fluid flow channel **740** maintaining the temperature of a different portion or component of the electrode **702**. In other embodiments, only one heat exchange fluid flow channel **740** may be included in the electrode **702**, e.g., coiled about the central axis thereof so as to extend along a portion or substantially an entirety of a length of the electrode **702** along the x-axis. In an example embodiment, the one or more heat exchange fluid flow channels **740** may be separate and fluidly decoupled from the plasma confinement chamber **706** and the internal reservoir **714**, and from the plurality of internal liquid flow channels **732** therebetween. In additional or alternative embodiments, an internal heating element/device **743** (e.g., depicted in FIGS. **8**A and **8**B as an internal heating coil, such as a mineral-insulated cable, interleaved with the one or more heat exchange fluid flow channels **740**, though other configurations are possible) may be thermally coupled to (e.g., positioned within) the internal reservoir **714** so as to emit heat and thereby provide greater control of temperature maintenance/modulation (e.g., heating and cooling functions may be split between the internal heating element/device **743** and the one or more heat exchange fluid flow channels **740**). In additional or alternative embodiments, an additional heating element/device (not shown at FIGS. **8**A and **8**B) may be thermally coupled to the liquid metal source **720**. In such embodiments, actuation of the additional heating element/device may adjust the temperature of the liquid metal **718** within the liquid metal source **720**, e.g., to melt/liquify the liquid metal **718** or otherwise adjust the liquid metal flow rate prior to the liquid metal **718** being flowed to the internal reservoir **714**.

[0139] In an example embodiment, the heat exchange fluid **741** may include one or more of a liquid metal (e.g., liquid lithium or mixtures therewith), a molten salt (e.g., as an insulating fluid), water, or an inert gas. Accordingly, in certain embodiments, one or both of the liquid metal **718** and the heat exchange fluid **741** may be liquid lithium.

[0140] During operation of the thermonuclear fusion reactor **701**, the plasma confinement chamber **706** may contain at least a portion of a fuel gas **744**, the fuel gas **744** fed to the plasma confinement chamber **706** via the one or more fuel gas supply channels **742** (e.g., formed as one or more conduits or pipes). Specifically, the one or more fuel gas supply channels **742** may fluidly couple the plasma confinement chamber **706** to one or more fuel gas sources **746** (e.g., one or more pressurized storage tanks), respectively, the one or more fuel gas sources **746** positioned external to the plasma confinement chamber **706**. The fuel gas **744** is depicted as arrows in FIG. **8**A, the arrows directed in a flow direction of the fuel gas **744** when the fuel gas **744** is being supplied to the plasma confinement chamber **706** during operation of the thermonuclear fusion reactor **701**. The one or more fuel gas sources **746** may contain any remaining portions of the fuel gas **744** (e.g., any remaining fuel gas **744** excepting the portion contained within the one or more fuel gas sources **746**), which may be controllably fed to the plasma confinement chamber **706** via actuation of one or more valves **748**, respectively (e.g., respectively controlled by one or more corresponding regulators; not shown at FIGS. **8**A and **8**B). Each of the one or more valves **748** is shown in FIG. **8**A in an open position to allow the fuel gas **744** to substantially freely flow to the plasma confinement chamber **706**, though each of the one or more valves **748** may also be independently placed in a closed position (see FIG. **8**B) to prevent the fuel gas **744** from flowing from the one or more fuel gas sources **746** to the plasma confinement chamber **706**. In some embodiments, each of the one or more valves **748** may be continuously variable, such that each of the one or more valves **748** may take on a range of partially open positions which permit greater flow than the closed position and less flow than the open position.

[0141] In an example embodiment, the fuel gas **744** may include any gas which may be ionized to form a plasma and which includes nucleons which may undergo thermonuclear fusion under practical conditions (e.g., conditions feasibly attainable in a laboratory or power plant setting). For example, the fuel gas **744** may include one or more of D_2 or T_2 (e.g., which may ionize to form nucleons which may undergo thermonuclear fusion via reaction (1)).

[0142] The liquid metal flow rate may be preselected and/or dynamically adjusted to maintain a predetermined thickness **738** of the protective film **736**, e.g., responsive to ablation thereof. For example, the liquid metal flow rate may deviate from the liquid metal ablation rate during operation of the thermonuclear fusion reactor **701**, e.g., the liquid metal flow rate may decrease as a result of the electrode **702** swelling due to cumulative neutron damage, the liquid metal ablation rate may decrease/increase responsive to corresponding decreases/increases in the discharge current or an intensity of the plasma arc **708**, etc. Accordingly, to maintain the predetermined thickness **738**, the liquid metal flow rate and changes thereto may be preselected and/or dynamically adjusted to match the liquid metal ablation rate. In some embodiments, the liquid metal flow rate may be preselected as a single value, which may be dynamically adjusted during operation of the thermonuclear fusion reactor **701**. In other embodiments, the liquid metal flow rate may be preselected as a series of values which follow from expected operation of the thermonuclear fusion reactor **701**.

[0143] In an example embodiment, the liquid metal flow rate may be adjusted responsive to deviating from the liquid metal ablation rate by greater than a threshold magnitude. Additionally or alternatively, an inert gas pressure within the internal reservoir **714** may be adjusted responsive to the liquid metal flow rate deviating from the liquid metal flow rate from the liquid metal ablation rate by greater than the threshold magnitude, where decreasing/increasing the inert gas pressure corresponding decreases/increases the liquid metal flow rate. In certain embodiments, the inert gas pressure may trend upwards (e.g., increase on average) over a lifetime use of the thermonuclear fusion reactor **701** to overcome increased flow resistance within the plurality of internal liquid flow channels **732** as the electrode body **702** swells due to cumulative neutron damage.

[0144] As an example, responsive to the liquid metal flow rate being lower than the liquid metal ablation rate by greater than the threshold magnitude, the liquid metal flow rate may be increased by one or more of adjusting the valve **722** from a partially open position or the closed position towards the open position to supply a greater amount of the liquid metal **718** from the liquid metal source **720**, adjusting the valve **730** from a partially open position or the closed position towards the open position to supply a greater amount of the inert gas **726** from the inert gas source **728**, increasing the heat exchange fluid flow rate in the one or more heat exchange fluid flow channels **740**, or increasing heat from the internal heating element/device **743**. Additionally or alternatively, responsive to the liquid metal flow rate being lower than the liquid metal ablation rate by greater than the threshold magnitude, the liquid metal ablation rate may be decreased by one or more of decreasing the fuel gas pressure by adjusting at least one of the one or more valves **748** from the open position or a partially open position towards the closed position, or decreasing the discharge current.

[0145] As another example, responsive to the liquid metal flow rate being higher than the liquid metal ablation rate by greater than the threshold magnitude, the liquid metal flow rate may be decreased by one or more of adjusting the valve **722** from the open position or a partially open position towards the closed position to supply a lesser amount of the liquid metal **718** from the liquid metal source **720**, adjusting the valve **730** from the open position or a partially open position towards the closed position to supply a lesser amount of the inert gas **726** from the inert gas source **728**, decreasing the heat exchange fluid flow rate in the one or more heat exchange fluid flow channels **740**, or decreasing heat from the internal heating element/device **743**. Additionally or alternatively, responsive to the liquid metal flow rate being higher than the liquid metal ablation rate by greater than the threshold magnitude, the liquid metal ablation rate may be increased by one or more of increasing the fuel gas pressure by adjusting at least one of the one or more valves **748** from a partially open position or the closed position towards the open position, or increasing the discharge current.

[0146] In some embodiments, a drain or a trough (not shown at FIGS. **8**A and **8**B) may be fluidically coupled to the plasma confinement chamber **706**. Upon ablation of the liquid metal **718** from the external surface **704*a***, at least a portion of the ablated liquid metal **718** may drop or flow into the drain or trough.

[0147] Prior to or following operation of the thermonuclear fusion reactor **701**, and as shown in FIG. **8**B, each of the valves **722**, **730**, and **748** may be in the closed position. Specifically, the valve **722** may be in the closed position to prevent the liquid metal **718** from flowing from the liquid metal source **720** to the internal reservoir **714**, the valve **730** may be in the closed position to prevent the inert gas **726** from flowing from the inert gas source **728** to the internal reservoir **714**, and each of the one or more valves **748** may be in the closed position to respectively prevent the fuel gas **744** from flowing from each of the one or more fuel gas sources **746** to the plasma confinement chamber **706**.

[0148] In some embodiments, the liquid metal **718** may be unable to flow from the internal reservoir **714** to the external surface **704*a*** when the liquid metal level **754** reaches or falls below the threshold level **756**. Accordingly, and as shown in FIG. **8**A, the liquid metal level **754** may be maintained above the threshold level **756** during operation of the thermonuclear fusion reactor **701**. However, and as shown in FIG. **8**B, responsive to the liquid metal level **754** reaching or falling below the threshold level **756**, the thermonuclear fusion reactor **701** may cease operation and no protective film **736** may be formed.

[0149] The thermonuclear fusion reactor **701** may include a controller or other computing device **750**, which may include non-transitory memory on which executable instructions may be stored.

[0150] The executable instructions may be executed by one or more processors of the controller **750** to perform various functionalities of the thermonuclear fusion reactor **701**. Accordingly, the executable instructions may include various routines for operation, maintenance, and testing of the thermonuclear fusion reactor **701**. The controller **750** may further include a user interface at which an operator of the thermonuclear fusion reactor **701** may enter commands or otherwise modify operation of the thermonuclear fusion reactor **701**. The user interface may include various components for facilitating operator use of the thermonuclear fusion reactor **701** and for receiving operator inputs (e.g., requests to generate plasma arcs for thermonuclear fusion, etc.), such as one or more displays, input devices (e.g., keyboards, touchscreens, computer mice, depressible buttons, mechanical switches or other depressible actuators, etc.), lights, etc. The controller **750** may be communicably coupled to various components (e.g., valves, power supplies, etc.) of the thermonuclear fusion reactor **701** to command actuation and use thereof (wired and/or wireless communication paths between the controller **750** and the various components are omitted from FIGS. **8**A and **8**B for clarity). For example, dynamic adjustment of the liquid metal flow rate may be based on one or more inputs (e.g., the liquid metal ablation rate, etc.) received at the controller **750**, whereat the one or more inputs may be correlated with one another and/or the liquid metal flow rate (e.g., via one or more neural networks stored in non-transitory memory). Based on the correlation, the controller **750** may output an adjustment to the liquid metal flow rate, which may be carried out via actuation of the various components of the thermonuclear fusion reactor **701** (e.g., to adjust the amount of the liquid metal **718** supplied to the internal reservoir **714**, to adjust the amount of the inert gas **726** supplied to the internal reservoir **714**, to adjust the heat exchange fluid flow rate, to adjust the heat from the internal heating element/device **743**, etc.).

[0151] The liquid metal source **720**, the inert gas source **728**, and the fuel gas sources **746** may be positioned along with various valves (e.g., the valves **722**, **730**, and **748**), control systems (e.g., the controller **750**), and other sensitive or complex components at a sufficient distance from the plasma confinement chamber **706** to mitigate component degradation due to high neutron flux during thermonuclear fusion. As such, lengthy piping (e.g., supply channels **716**, **724**, and **742**), wires, cables, and other couplings or communication lines may be extended between the plasma confinement chamber **706** (and the electrode **702** at least partially enclosed therein) and the various sensitive and complex components described above.

[0152] As discussed hereinabove, the electrode **702** may be formed in a substantially cylindrical shape having the tapered, rounded nosecone **704**. The substantially cylindrical shape (including the nosecone **704**) may be radially symmetric with respect to the x-axis, with the cross-section of FIGS. **8**A and **8**B being taken at a widest portion of the substantially cylindrical shape along the y-axis. Moreover, components depicted in the schematic cross-sectional diagrams of FIGS. **8**A and **8**B may be replicated about the x-axis so as to be radially symmetrically distributed within one or more planes containing the x-axis. For example, the plurality of internal liquid flow channels **732** and/or the one or more fuel gas supply channels **742** may be regularly spaced about the x-axis (e.g., at an angle, such as 60°, 90°, etc., relative to one another).

[0153] Referring now to FIGS. **9**A and **9**B, block diagrams of a method **800** for operating a plasma confinement system of a thermonuclear fusion reactor, such as any of the plasma confinement systems described in detail above with reference to FIGS. **1-4**, **8**A, and **8**B, are shown. In an example embodiment, the plasma confinement system may include an in situ renewable electrode including a protective film of a flowing, liquid metal which may ablate from an external surface of the electrode upon interaction with a plasma arc generated by and confined within the plasma confinement system. Specifically, and as described below, the protective film may be continually (e.g., without interruption or with appreciably no delay) replenished responsive to the ablation, such that high-discharge erosion of an external surface of the electrode resulting from the plasma arc interaction may be mitigated or altogether obviated.

[0154] In some embodiments, the method **800**, or a portion thereof, may be implemented as executable instructions stored in non-transitory memory of a computing device, such as a controller communicably coupled to the plasma confinement system. Moreover, in certain embodiments, additional or alternative sequences of steps may be implemented as executable instructions on such a computing device, where individual steps discussed with reference to the method **800** may be added, removed, substituted, modified or interchanged.

[0155] Referring now to FIG. **9**A, at block **802**, the method **800** may include generating a request to initialize the plasma confinement system, according to which an initialization phase of the plasma confinement system may be initiated. In an example embodiment, the request may be generated responsive to receiving a user input, e.g., from an operator of the plasma confinement system. For instance, initialization of the plasma confinement system may be triggered or otherwise initiated via an operator interacting with a user interface, e.g., a push button switch, toggle switch, or other mechanical actuator, a keyboard, a touchscreen, a cursor input, etc.

[0156] At block **804**, the method **800** may include flowing the liquid metal from an internal reservoir of the electrode to the external surface of the electrode at a liquid metal flow rate, e.g., during the initialization phase. In an example embodiment, once the liquid metal reaches the external surface, the liquid metal may form a protective film or meniscus between the external surface and a plasma confinement chamber including the electrode (e.g., at and around a central axis of the plasma confinement chamber where the plasma arc, once generated, may interact with the electrode).

[0157] The liquid metal flow rate may be preselected, e.g., by the operator of the plasma confinement system, based on one or more operating conditions of the plasma confinement system. For example, the one or more operating conditions may include an inert gas pressure in the internal reservoir, a liquid metal level in the internal reservoir, a liquid metal temperature, an amount of the fuel gas provided to the plasma confinement chamber, a magnitude of a Z-pinch discharge current applied to the plasma (see block **814** below), etc. Specifically, at block **806**, the liquid metal may be supplied to the internal reservoir up to the liquid metal level. For example, a first valve opening may be increased to permit the liquid metal to flow into the internal reservoir from a liquid metal source. At block **808**, an inert gas may be supplied to the internal reservoir until the inert gas pressure is met. For example, a second valve opening may be increased to permit the inert gas to flow into the internal reservoir from an inert gas source. At block **810**, a liquid metal temperature may be maintained, e.g., within the internal reservoir. For example, a heat exchange fluid may be flowed through the electrode, e.g., via a flow channel which may be positioned to transfer heat to and from the liquid metal, and/or adjusting heat from an internal heating coil of the electrode, e.g., which may be positioned within the internal reservoir. In some embodiments, the heat exchange fluid may be flowed through the electrode and/or the internal heating coil may be heated prior to flowing of the liquid metal and generation of the plasma arc so as to preheat the electrode for use. Each of the liquid metal level, the inert gas pressure, and the liquid metal temperature may be preselected upon initiation of the plasma confinement system (e.g., according to the request to initialize the plasma confinement system) and/or dynamically adjusted during operation of the plasma confinement system. In an example embodiment, the liquid metal level, the inert gas pressure, and the liquid metal temperature may be judiciously balanced with one another to attain and maintain the liquid metal flow rate.

[0158] At block **812**, the method **800** may include initiating a plasma arc generation phase of the plasma confinement system, e.g., following the initialization phase. Specifically, in an example embodiment, the plasma arc generation phase may be initiated at least by powering up the plasma confinement system (e.g., one or more power supplies may supply power to various components utilized during the plasma arc generation phase) and providing fuel gas for forming a plasma to the plasma confinement chamber by increasing one or more third valve openings. In an example embodiment, the fuel gas may include one or more of D_2 or T_2.

[0159] Continuing now to FIG. **9**B, at block **814**, the method **800** may include generating the plasma arc in the plasma confinement chamber, e.g., during the plasma arc generation phase. In an example embodiment, the Z-pinch discharge current may be applied at a repetition rate between a pair of electrodes, the pair of electrodes including the in situ renewable electrode, to generate the plasma arc. Accordingly, during operation of the plasma confinement system, the in situ renewable electrode may function as either a cathode in some embodiments or an anode in other embodiments. The plasma arc may be confined, compressed, and sustained via an axially symmetric magnetic field generated by the Z-pinch discharge current, with the Z-pinch discharge current stabilized by a sheared ion velocity flow created and maintained via an applied residual current. As a result of the plasma arc generation, the pair of electrodes may be heated and bombarded with deuterium, tritium, and free neutrons (e.g., resulting from thermonuclear fusion within the plasma arc). More specifically, as the Z-pinch discharge current is increased, each of a temperature of the electrode may be increased and an increased amount of deuterium, tritium, and free neutrons may bombard the electrode, for example. However, the in situ renewable electrode may mitigate or altogether obviate erosion of the external surface of the electrode during such bombardment by continually replenishing the external surface of the electrode.

[0160] Specifically, at block **816**, the method **800** may include ablating the liquid metal from the external surface of the electrode (e.g., rather than the external surface of the electrode itself) at a liquid metal ablation rate via the plasma arc. Specifically, application of the Z-pinch discharge current to the electrode, in addition to neutronic bombardment from the plasma arc in some cases, may result in the ablation of the liquid metal from the external surface of the electrode. The liquid metal may be continually (e.g., without interruption or with no appreciable delay) replenished at the external surface from the internal reservoir.

[0161] At block **818**, the method **800** may include determining whether the liquid metal level is less than or equal to a threshold level. In an example embodiment, the threshold level may be a level in the internal reservoir at which the liquid metal may no longer be supplied to the external surface at a desired liquid metal flow rate. As such, in some examples, the threshold level may be dynamically adjusted based on desired operation of the plasma confinement system.

[0162] If the liquid metal level is greater than the threshold level, the method **800** may proceed to block **820**, where the method **800** may include determining whether to adjust the repetition rate of the Z-pinch discharge current, e.g., according to a request generated at the plasma confinement system.

[0163] If adjustment to the repetition rate is indicated, the method **800** may proceed to block **822**, where the method **800** may include adjusting the repetition rate of the Z-pinch discharge current. In an example embodiment, the repetition rate may be adjusted based on desired power generation, e.g., as indicated in the request to adjust the repetition rate. As an example, the repetition rate may be increased responsive to the request to adjust the repetition rate indicating increased power production. As another example, the repetition rate may be decreased responsive to the request to adjust the repetition rate indicating decreased power production. As such, in such examples, the request to adjust the repetition rate may indicate adjusting the power generation (e.g., a request may be generated to adjust the power generation, which may result in the repetition rate being correspondingly adjusted).

[0164] Moreover, the liquid metal ablation rate may be adjusted as a result of the repetition rate being adjusted. As an example, the liquid metal ablation rate may increase (e.g., less of the liquid metal may be retained on the external surface of the electrode) as a result of the repetition rate being increased. As another example, the liquid metal ablation rate may decrease (e.g., more of the liquid metal may be retained on the external surface of the electrode) as a result of the repetition rate being decreased. As such, the request to adjust the repetition rate may indicate adjusting the liquid metal ablation rate (e.g., a request to adjust the liquid metal ablation rate may be generated, which may result in the repetition rate being correspondingly adjusted).

[0165] At block **824**, the method **800** may include adjusting the liquid metal flow rate. As an example, the liquid metal flow rate may be adjusted responsive to the repetition rate being adjusted (see block **822** above). As another example, the liquid metal flow rate may be adjusted responsive to the liquid metal flow rate deviating from the liquid metal ablation rate by a threshold magnitude (see block **826** below). The liquid metal flow rate may be nonzero prior to and following adjusting the liquid metal flow rate, e.g., as the plasma confinement system may be operating immediately prior to and immediately following block **824**. Accordingly, prior to the adjustment, the liquid metal flow rate may be a first nonzero value, and, following the adjustment, the liquid metal flow rate may be second nonzero value, the second nonzero value different from the first nonzero value.

[0166] In an example embodiment, adjusting the liquid metal flow rate may include adjusting one or more of the liquid metal level in the internal reservoir, the inert gas pressure in the internal reservoir, or the liquid metal temperature. As an example, increasing the liquid metal flow rate may include increasing one or more of the liquid metal level, the inert gas pressure, or the liquid metal temperature. As another example, decreasing the liquid metal flow rate may include decreasing one or more of the liquid metal level, the inert gas pressure, or the liquid metal temperature. In certain embodiments, adjusting the inert gas pressure may include increasing, on average (e.g., increasing by a net amount), the inert gas pressure over a lifetime use of the electrode, e.g., responsive to cumulative neutron damage swelling the electrode. In certain embodiments, the liquid metal flow rate may be adjusted in a feedforward manner, such that dynamic changes in the plasma confinement system detected during prior use sessions or earlier discharge during the same use session (e.g., after a brief delay, such as 0.5 s) may be accounted for. The method **800** may return to block **814** to continue generating the plasma arc in the plasma confinement chamber.

[0167] If no adjustment to the repetition rate is indicated (see block **820** above), the method **800** may proceed to block **826**, where the method **800** may include determining whether the liquid metal flow rate has deviated from the liquid metal ablation rate by greater than the threshold magnitude.

[0168] In an example embodiment, the liquid metal flow rate may match the liquid metal ablation rate such that the protective film or meniscus on the external surface of the electrode may be maintained at a consistent thickness. Accordingly, if the liquid metal flow rate deviates from the liquid metal ablation rate by greater than the threshold magnitude, the method **800** may proceed to block **824**, where the method **800** may include adjusting the liquid metal flow rate (as described above).

[0169] If the liquid metal flow rate is maintained within the threshold magnitude of the liquid metal ablation rate, the method **800** may proceed to block **828**, where the method **800** may include determining whether to stop the plasma arc generation, e.g., according to a request generated at the plasma confinement system. If no stopping of the plasma arc generation is indicated, the method **800** may return to block **814** to continue generating the plasma arc in the plasma confinement chamber.

[0170] If stopping plasma arc generation is indicated or if the liquid metal level is less than or equal to the threshold level (see block **818** above), the method **800** may proceed to block **830**, where the method **800** may include stopping plasma arc generation. Specifically, the Z-pinch discharge current may cease being applied to the plasma and the one or more third valve openings may be decreased or altogether closed to reduce or cease supplying the fuel gas to the plasma confinement chamber, such that the plasma arc may become unsustainable and cease.

[0171] At block **832**, the method **800** may include ceasing flow of the liquid metal, e.g., from the internal reservoir to the external surface of the electrode. For example, the first valve opening may be closed to cease supplying the liquid metal to the internal reservoir and thereby to the external surface. In some embodiments, upon ceasing flow of the liquid metal, the liquid metal may be cleared from the internal reservoir and one or more internal channels fluidly coupled thereto via purging with a gas, e.g., the inert gas.

[0172] At block **834**, the method **800** may include removing at least a portion of the liquid metal from the external surface of the electrode, e.g., relative to an amount of the liquid metal present during the plasma arc generation phase. In an example embodiment, the liquid metal may be removed by increasing the liquid metal temperature (e.g., by increasing flow of the heat exchange fluid through the electrode and/or by increasing heat from the internal heating coil), such that the liquid metal flow rate may be increased at the external surface (even absent the plasma arc interacting with the external surface). As such, following plasma arc generation and ceasing flow of the liquid metal to the external surface, the liquid metal may flow off of the external surface and collect within the plasma confinement chamber, e.g., within a trough, and/or exit the plasma confinement chamber, e.g., via a drain.

[0173] Following liquid metal removal, in some embodiments, a smaller amount of the liquid metal may remain on the external surface of the electrode relative to an amount of the liquid metal present on the external surface during operation of the plasma confinement system. In one embodiment, all or substantially all of the liquid metal is removed from the external surface following liquid metal removal. For example, none of the liquid metal may be visibly present (e.g., to a human eye) on the external surface following liquid metal removal. In an additional or alternative embodiment, a small portion of the liquid metal may be present (e.g., visibly present) on the external surface following liquid metal removal, but not in an amount sufficient to practically affect future operation of the plasma confinement system. In other embodiments, a portion of the liquid metal may be present on the external surface following liquid metal removal, e.g., to protect the body of the electrode from erosion during future operation of the plasma confinement system.

[0174] Embodiments of the present disclosure can be described in view of the following clauses:

[0175] 1. A plasma confinement system, including:

[0176] a plurality of electrodes, each electrode of the plurality of electrodes arranged coaxially with respect to an assembly region of the plasma confinement system and positioned so as to be exposed to the assembly region,

[0177] wherein one or more electrodes of the plurality of electrodes includes an electrode material which releases hydrogen gas above a threshold temperature.

[0178] 2. The plasma confinement system of clause 1, wherein the plurality of electrodes includes:

[0179] a first electrode positioned to define at least a portion of an outer boundary of the assembly region; and

[0180] a second electrode positioned to define one end of the assembly region.

[0181] 3. The plasma confinement system of clause 2, wherein the plurality of electrodes further includes a third electrode positioned at a same end of the assembly region defined by the second electrode or an end of the assembly region opposite to the end of the assembly region defined by the second electrode.

[0182] 4. The plasma confinement system of any one of clauses 2 or 3, wherein the second electrode includes a nosecone exposed to the assembly region so as to be intersected by a plasma arc axis coaxial with each electrode of the plurality of electrodes, and wherein the nosecone includes the electrode material.

[0183] 5. The plasma confinement system of any one of clauses 1-4, wherein the electrode material includes one or more of a metal deuteride or a metal tritide.

[0184] 6. The plasma confinement system of clause 5, wherein the one or more of the metal deuteride or the metal tritide includes one or more of Ti, Zr, Sc, Mg, V, ^{6}Li, or any alloy formed by any combination of one or more of Ti, Zr, Sc, Mg, V, or ^{6}Li.

[0185] 7. The plasma confinement system of any one of clauses 1-6, wherein the electrode material releases free neutrons upon ionic bombardment of the electrode material.

[0186] 8. The plasma confinement system of any one of clauses 1-7, wherein the electrode material releases free tritium atoms upon neutronic bombardment of the electrode material.

[0187] 9. The plasma confinement system of any one of clauses 2, 3, 5, 6, 7, or 8, wherein the second electrode includes:

[0188] a nosecone exposed to the assembly region so as to be intersected by a plasma arc axis coaxial with each electrode of the plurality of electrodes, optionally wherein the nosecone includes the electrode material; and

[0189] a liquid metal, a portion of the liquid metal forming a protective film between a surface of the nosecone and the assembly region during operation of the plasma confinement system.

[0190] 10. A thermonuclear fusion reactor, including:

[0191] a plasma confinement chamber;

[0192] an inner electrode; and

[0193] an outer electrode at least partially surrounding the inner electrode; and

[0194] wherein one or both of the inner electrode or the outer electrode includes a metal hydride to release a fuel gas between the inner electrode and the outer electrode to contribute plasma to a thermonuclear fusion process of the thermonuclear fusion reactor.

[0195] 11. The thermonuclear fusion reactor of clause 10, wherein one or both of the inner electrode and the outer electrode includes one or more valves which route additional fuel gas to the plasma confinement chamber during operation of the thermonuclear fusion reactor.

[0196] 12. The thermonuclear fusion reactor of any one of clauses 10 or 11, wherein the metal hydride decomposes to a metal and the fuel gas when heated to a decomposition temperature.

[0197] 13. The thermonuclear fusion reactor of clause 12, wherein the metal includes one or more of Ti, Zr, Sc, Mg, V, ^{6}Li, or any alloy formed by any combination thereof, and wherein the fuel gas includes one or more of D_2 or T_2.

[0198] 14. The thermonuclear fusion reactor of any one of clauses 10-13, wherein the metal hydride expels free neutrons upon ionic bombardment with deuterium and/or tritium.

[0199] 15. The thermonuclear fusion reactor of any one of clauses 10-14, wherein the metal hydride expels free tritium atoms upon neutronic bombardment.

[0200] 16. A method, including:

[0201] generating a thermonuclear fusion reaction in a thermonuclear fusion reactor by:

[0202] heating an electrode formed from a bulk material and a metal layer evaporated thereon, the metal layer loaded with deuterium and/or tritium, to cause the electrode to release hydrogen gas;

[0203] forming, using the hydrogen gas, plasma inside the thermonuclear fusion reactor; and

[0204] using electrical current directed into the plasma via the electrode to compress the plasma to produce the thermonuclear fusion reaction.

[0205] 17. The method of clause 16, wherein the metal layer is evaporated onto the bulk material by masking the bulk material to evaporate the metal layer on only an unmasked portion of the bulk material.

[0206] 18. The method of any one of clauses 16 or 17, wherein the bulk material forms a shaft ending in a nosecone, and wherein the metal layer is evaporated onto only the nosecone.

[0207] 19. The method of any one of clauses 16-18, wherein the metal layer includes Ti, Zr, Sc, and/or ^{6}Li.

[0208] 20. The method of any one of clauses 16-19, wherein a thickness of the metal layer is less than a millimeter.

[0209] 21. A plasma confinement system, including:

[0210] a plasma confinement chamber; and

[0211] an electrode body, including:

[0212] a nosecone positioned so as to be exposed to the plasma confinement chamber;

[0213] an internal reservoir fluidly coupled to a liquid metal source which supplies a liquid metal to the internal reservoir during operation of the plasma confinement system; and

[0214] a plurality of internal liquid flow channels extending to a surface of the nosecone so as to fluidly couple the internal reservoir to the plasma confinement chamber.

[0215] 22. The plasma confinement system of clause 21, wherein a first portion of the liquid metal forms a protective film between the surface of the nosecone and the plasma confinement chamber during operation of the plasma confinement system, and wherein a remaining, second portion of the liquid metal is fed from the liquid metal source to the internal reservoir and along the plurality of internal liquid flow channels towards the surface of the nosecone during operation of the plasma confinement system.

[0216] 23. The plasma confinement system of clause 22, wherein the protective film is maintained at a predetermined thickness during operation of the plasma confinement system.

[0217] 24. The plasma confinement system of any one of clauses 21-23, wherein the electrode body is formed from one or more of a metal, graphite, or a semiconductor.

[0218] 25. The plasma confinement system of any one of clauses 21-24, wherein the electrode body is coaxial with a direction of gravity, wherein the nosecone is positioned below the internal reservoir with respect to the direction of gravity, and whereupon extending from the internal reservoir, each internal liquid flow channel of the plurality of internal liquid flow channels is initially oriented upwards and opposite to the nosecone, wherefrom each internal liquid flow channel of the plurality of internal liquid flow channels arches downwards and towards the nosecone.

[0219] 26. The plasma confinement system of any one of clauses 22-25, wherein:

[0220] each internal liquid flow channel of the plurality of internal liquid flow channels includes:

[0221] a main liquid flow channel fluidly coupled to and extending from the internal reservoir; and

[0222] a plurality of liquid flow capillaries which fluidly couples the main liquid flow channel to the plasma confinement chamber, where the protective film is retained on the surface of the nosecone via capillary action induced by the plurality of liquid flow capillaries.

[0223] 27. The plasma confinement system of any one of clauses 21-26, wherein the electrode body forms one electrode of a plurality of electrodes positioned so as to be exposed to the plasma confinement chamber, and wherein one or more electrodes of the plurality of electrodes includes an electrode material which releases hydrogen gas to be used in plasma generation above a threshold temperature.

[0224] 28. A thermonuclear fusion reactor, including:

[0225] a plasma confinement chamber;

[0226] an electrode at least partially enclosed within the plasma confinement chamber, the electrode including a nosecone which intersects with an axis of a plasma arc confined within the plasma confinement chamber during operation of the thermonuclear fusion reactor; and

[0227] a liquid metal meniscus formed on a surface of the nosecone, the liquid metal meniscus directly interacting with the confined plasma arc during operation of the thermonuclear fusion reactor.

[0228] 29. The thermonuclear fusion reactor of clause 28, wherein the electrode includes a plurality of internal channels and an internal reservoir, the internal reservoir in fluidic communication with the liquid metal meniscus via at least a first portion of the plurality of internal channels.

[0229] 30. The thermonuclear fusion reactor of clause 29, wherein a second portion of the plurality of internal channels supplies a fuel gas to the plasma confinement chamber.

[0230] 31. The thermonuclear fusion reactor of any one of clauses 29 or 30, wherein a third portion of the plurality of internal channels contains a heat exchange fluid which maintains a temperature of the electrode and/or the liquid metal meniscus.

[0231] 32. The thermonuclear fusion reactor of any one of clauses 29-31, further including a first supply channel fluidly coupling the internal reservoir to a liquid metal source, the liquid metal source positioned external to the plasma confinement chamber.

[0232] 33. The thermonuclear fusion reactor of clause 32, further including a second supply channel fluidly coupling the internal reservoir to an inert gas source, the inert gas source positioned external to the plasma confinement chamber.

[0233] 34. A method, including:

[0234] flowing a liquid metal from an internal reservoir of an electrode to an external surface of the electrode at a liquid metal flow rate;

[0235] generating a confined plasma arc to ablate the liquid metal from the external surface at a liquid metal ablation rate; and

[0236] responsive to the liquid metal flow rate deviating from the liquid metal ablation rate by greater than a threshold magnitude, adjusting the liquid metal flow rate by adjusting one or more of a liquid metal level in the internal reservoir, an inert gas pressure in the internal reservoir, or a liquid metal temperature.

[0237] 35. The method of clause 34, wherein flowing the liquid metal at the liquid metal flow rate includes:

[0238] supplying the liquid metal to the internal reservoir up to the liquid metal level; and

[0239] supplying an inert gas to the internal reservoir until the inert gas pressure is met.

[0240] 36. The method of any one of clauses 34 or 35, wherein flowing the liquid metal at the liquid metal flow rate includes maintaining the liquid metal temperature by flowing a heat exchange fluid through the electrode and/or adjusting heat from an internal heating coil of the electrode.

[0241] 37. The method of any one of clauses 34-36, wherein adjusting the inert gas pressure includes increasing, on average, the inert gas pressure over a lifetime use of the electrode.

[0242] 38. The method of any one of clauses 34-37, wherein the liquid metal flow rate is nonzero prior to and following adjusting the liquid metal flow rate.

[0243] 39. The method of any one of clauses 34-38, further including:

[0244] responsive to the liquid metal level being less than or equal to a threshold level:

[0245] ceasing flow of the liquid metal from the internal reservoir; and

[0246] removing at least a portion of the liquid metal from the external surface by increasing the liquid metal temperature.

[0247] 40. The method of any one of clauses 34-39, further including adjusting the liquid metal ablation rate by adjusting a repetition rate of a discharge current sustaining the confined plasma arc.

[0248] The specification and drawings are to be regarded in an illustrative rather than a restrictive sense. It will, however, be evident that various modifications and changes may be made thereunto without departing from the broader spirit and scope of the invention as set forth in the claims.

[0249] Other variations are within the spirit of the present disclosure. Thus, while the disclosed techniques are susceptible to various modifications and alternative constructions, certain illustrated embodiments thereof are shown in the drawings and have been described above in detail. It should be understood, however, that there is no intention to limit the invention to the specific form or forms disclosed but, on the contrary, the intention is to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention, as defined in the appended claims.

[0250] The use of the terms "a" and "an" and "the" and similar referents in the context of describing the disclosed embodiments (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. Similarly, use of the term "or" is to be construed to mean "and/or" unless contradicted explicitly or by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. The term "connected," when unmodified and referring to physical connections, is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. The use of the term "set" (e.g., "a set of items") or "subset" unless otherwise noted or contradicted by context, is to be construed as a nonempty collection comprising one or more members. Further, unless otherwise noted or contradicted by context, the term "subset" of a corresponding set does not necessarily denote a proper subset of the corresponding set, but the subset and the corresponding set may be equal. The use of the phrase "based on," unless otherwise explicitly stated or clear from context, means "based at least in part on" and is not limited to "based solely on."

[0251] Conjunctive language, such as phrases of the form "at least one of A, B, and C," or "at least one of A, B and C," (i.e., the same phrase with or without the Oxford comma) unless specifically stated otherwise or otherwise clearly contradicted by context, is otherwise understood within the context as used in general to present that an item, term, etc., may be either A or B or C, any nonempty subset of the set of A and B and C, or any set not contradicted by context or otherwise excluded that contains at least one A, at least one B, or at least one C. For instance, in the illustrative example of a set having three members, the conjunctive phrases "at least one of A, B, and C" and "at least one of A, B and C" refer to any of the following sets: {A}, {B}, {C}, {A, B}, {A, C}, {B, C}, {A, B, C}, and, if not contradicted explicitly or by context, any set having {A}, {B}, and/or {C} as a subset (e.g., sets with multiple "A"). Thus, such conjunctive language is not generally intended to imply that certain embodiments require at least one of A, at least one of B and at least one of C each to be present. Similarly, phrases such as "at least one of A, B, or C" and "at least one of A, B or C" refer to the same as "at least one of A, B, and C" and "at least one of A, B and C" refer to any of the following sets: {A}, {B}, {C}, {A, B}, {A, C}, {B, C}, {A, B, C}, unless differing meaning is explicitly stated or clear from context. In addition, unless otherwise noted or contradicted by context, the term "plurality" indicates a state of being plural (e.g., "a plurality of items" indicates multiple items). The number of items in a plurality is at least two but can be more when so indicated either explicitly or by context.

[0252] Operations of processes described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. In an embodiment, a process such as those processes described herein (or variations and/or combinations thereof) is performed under the control of one or more computer systems configured with executable instructions and is implemented as code (e.g., executable instructions, one or more computer programs or one or more applications) executing collectively on one or more processors, by hardware or combinations thereof. In an embodiment, the code is stored on a computer-readable storage medium, for example, in the form of a computer program comprising a plurality of instructions executable by one or more processors. In an embodiment, a computer-readable storage medium is a non-transitory computer-readable storage medium that excludes transitory signals (e.g., a propagating transient electric or electromagnetic transmission) but includes non-transitory data storage circuitry (e.g., buffers, cache, and queues) within transceivers of transitory signals. In an embodiment, code (e.g., executable code or source code) is stored on a set of one or more non-transitory computer-readable storage media having stored thereon executable instructions that, when executed (i.e., as a result of being executed) by one or more processors of a computer system, cause the computer system to perform operations described herein. The set of non-transitory computer-readable storage media, in an embodiment, comprises multiple non-transitory computer-readable storage media, and one or more of individual non-transitory storage media of the multiple non-transitory computer-readable storage media lack all of the code while the multiple non-transitory computer-readable storage media collectively store all of the code. In an embodiment, the executable instructions are executed such that different instructions are executed by different processors—for example, in an embodiment, a non-transitory computer-readable storage medium stores instructions and a main CPU executes some of the instructions while a graphics processor unit executes other instructions. In another embodiment, different components of a computer system have separate processors and different processors execute different subsets of the instructions.

[0253] Accordingly, in an embodiment, computer systems are configured to implement one or more services that singly or collectively perform operations of processes described herein, and such computer systems are configured with applicable hardware and/or software that enable the performance of the operations. Further, a computer system, in an embodiment of the present disclosure, is a single device and, in another embodiment, is a distributed computer system comprising multiple devices that operate differently such that the distributed computer system performs the operations described herein and such that a single device does not perform all operations.

[0254] The use of any and all examples or exemplary language (e.g., "such as") provided herein is intended merely to better illuminate embodiments of the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0255] Embodiments of this disclosure are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for embodiments of the present disclosure to be practiced otherwise than as specifically described herein. Accordingly, the scope of the present disclosure includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the scope of the present disclosure unless otherwise indicated herein or otherwise clearly contradicted by context.

[0256] All references including publications, patent applications, and patents cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

1. A plasma confinement system, comprising:

a plurality of electrodes, each electrode of the plurality of electrodes arranged coaxially with respect to an assembly region of the plasma confinement system and positioned so as to be exposed to the assembly region,

wherein one or more electrodes of the plurality of electrodes comprises an electrode material which releases hydrogen gas above a threshold temperature.

2. The plasma confinement system of claim **1**, wherein the plurality of electrodes comprises:

a first electrode positioned to define at least a portion of an outer boundary of the assembly region; and

a second electrode positioned to define one end of the assembly region.

3. The plasma confinement system of claim **2**, wherein the plurality of electrodes further comprises a third electrode positioned at a same end of the assembly region defined by the second electrode or an end of the assembly region opposite to the end of the assembly region defined by the second electrode.

4. The plasma confinement system of claim **2**, wherein the second electrode comprises a nosecone exposed to the assembly region so as to be intersected by a plasma arc axis coaxial with each electrode of the plurality of electrodes, and wherein the nosecone comprises the electrode material.

5. The plasma confinement system of claim **1**, wherein the electrode material comprises one or more of a metal deuteride or a metal tritide.

6. The plasma confinement system of claim **5**, wherein the one or more of the metal deuteride or the metal tritide comprises one or more of Ti, Zr, Sc, Mg, V, ^{6}Li, or any alloy formed by any combination of one or more of Ti, Zr, Sc, Mg, V, or ^{6}Li.

7. The plasma confinement system of claim **1**, wherein the electrode material releases free neutrons upon ionic bombardment of the electrode material.

8. The plasma confinement system of claim **1**, wherein the electrode material releases free tritium atoms upon neutronic bombardment of the electrode material.

9. The plasma confinement system of claim **2**, wherein the second electrode comprises:

a nosecone exposed to the assembly region so as to be intersected by a plasma arc axis coaxial with each electrode of the plurality of electrodes; and

a liquid metal, a portion of the liquid metal forming a protective film between a surface of the nosecone and the assembly region during operation of the plasma confinement system.

10. A thermonuclear fusion reactor, comprising:

a plasma confinement chamber;

an inner electrode; and

an outer electrode at least partially surrounding the inner electrode; and

wherein one or both of the inner electrode or the outer electrode comprises a metal hydride to release a fuel gas between the inner electrode and the outer electrode to contribute plasma to a thermonuclear fusion process of the thermonuclear fusion reactor.

11. The thermonuclear fusion reactor of claim **10**, wherein one or both of the inner electrode and the outer electrode comprises one or more valves which route additional fuel gas to the plasma confinement chamber during operation of the thermonuclear fusion reactor.

12. The thermonuclear fusion reactor of claim **10**, wherein the metal hydride decomposes to a metal and the fuel gas when heated to a decomposition temperature.

13. The thermonuclear fusion reactor of claim **12**, wherein the metal comprises one or more of Ti, Zr, Sc, Mg, V, ^{6}Li, or any alloy formed by any combination thereof, and wherein the fuel gas comprises one or more of D_2 or T^2.

14. The thermonuclear fusion reactor of claim **10**, wherein the metal hydride expels free neutrons upon ionic bombardment with deuterium and/or tritium.

15. The thermonuclear fusion reactor of claim **10**, wherein the metal hydride expels free tritium atoms upon neutronic bombardment.

16. A method, comprising:

generating a thermonuclear fusion reaction in a thermonuclear fusion reactor by:

heating an electrode formed from a bulk material and a metal layer evaporated thereon, the metal layer loaded with deuterium and/or tritium, to cause the electrode to release hydrogen gas;

forming, using the hydrogen gas, plasma inside the thermonuclear fusion reactor; and

using electrical current directed into the plasma via the electrode to compress the plasma to produce the thermonuclear fusion reaction.

17. The method of claim **16**, wherein the metal layer is evaporated onto the bulk material by masking the bulk material to evaporate the metal layer on only an unmasked portion of the bulk material.

18. The method of claim **16**, wherein the bulk material forms a shaft ending in a nosecone, and wherein the metal layer is evaporated onto only the nosecone.

19. The method of claim **16**, wherein the metal layer comprises Ti, Zr, Sc, and/or ^{6}Li.

20. The method of claim **16**, wherein a thickness of the metal layer is less than a millimeter.

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