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(54) **APPARATUS AND METHOD FOR SOURCING FUSION REACTION PRODUCTS**

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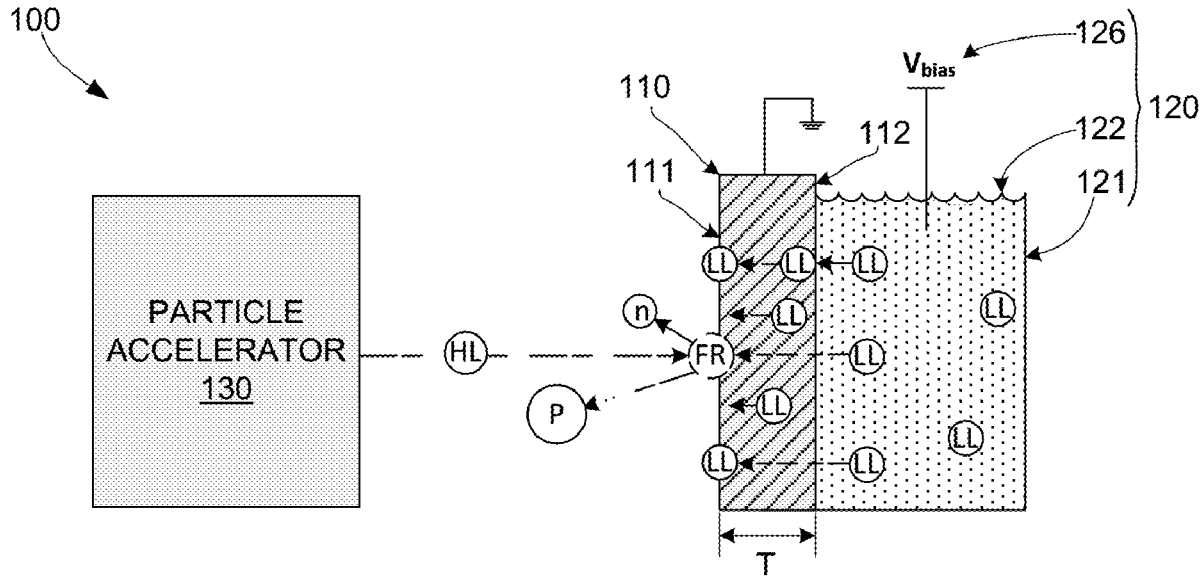
(57) **ABSTRACT**

An apparatus and method for sourcing nuclear fusion products uses an electrochemical loading process to load low-kinetic-energy (low-k) light element particles into a target electrode, which comprises a light-element-absorbing material (e.g., Palladium). An electrolyte solution containing the low-k light element particles is maintained in contact with a backside surface of the target electrode while a bias voltage is applied between the target electrode and an electrochemical anode, thereby causing low-k light element particles to diffuse from the backside surface to an opposing frontside surface of the target electrode. High-kinetic-energy (high-k) light element particles are directed against the frontside, thereby causing fusion reactions each time a high-k light element particle operably collides with a low-k light element particle disposed on the frontside surface. Fusion reaction rates are controlled by adjusting the bias voltage.



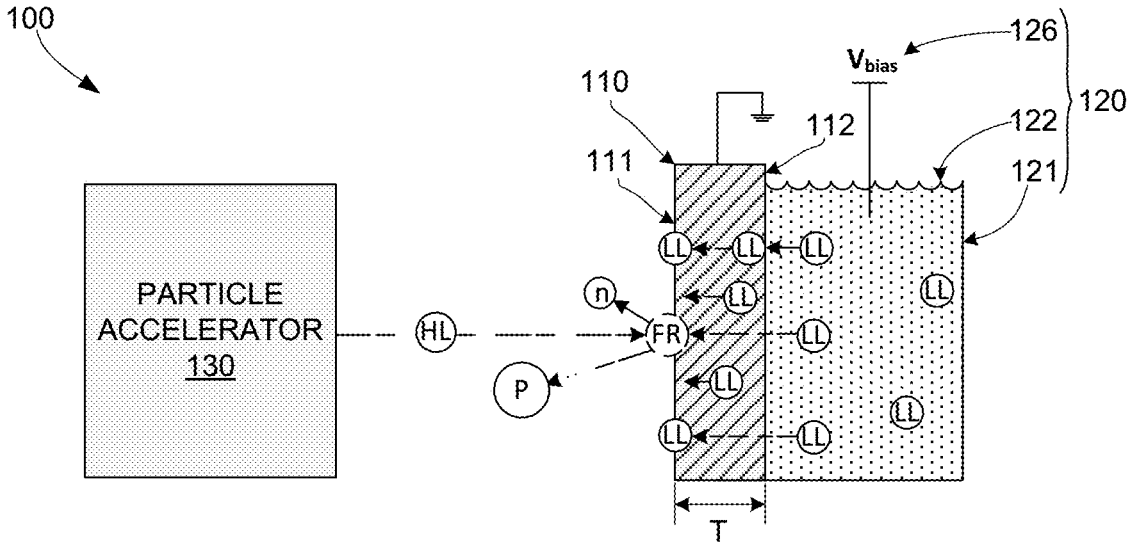

100
126
V_{bias}
110
120
112
122
111
121
PARTICLE ACCELERATOR 130
HL
n
FR
P
LL
T

FIG. 1

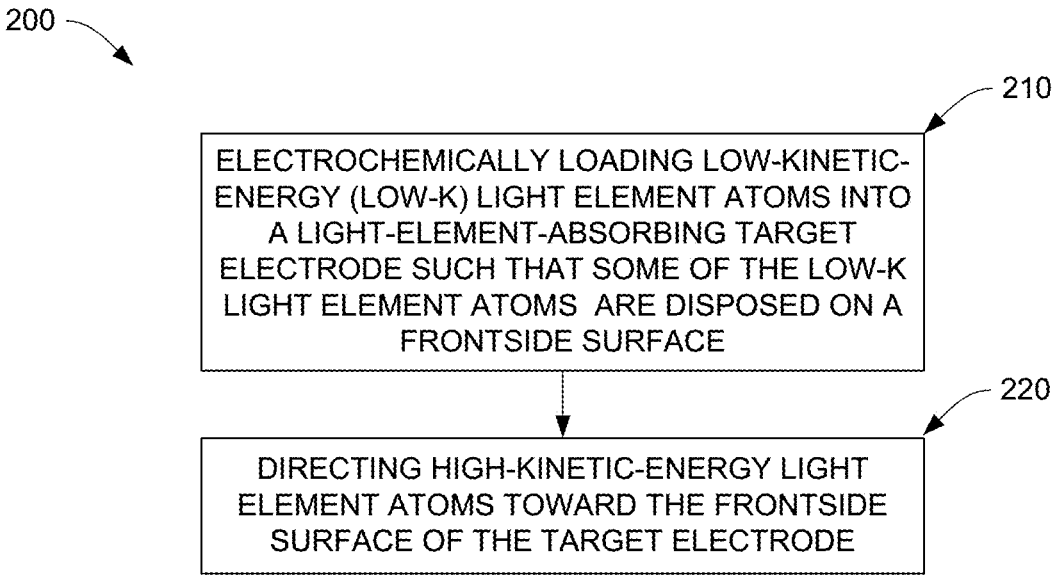

200
210
ELECTROCHEMICALLY LOADING LOW-KINETIC-ENERGY (LOW-K) LIGHT ELEMENT ATOMS INTO A LIGHT-ELEMENT-ABSORBING TARGET ELECTRODE SUCH THAT SOME OF THE LOW-K LIGHT ELEMENT ATOMS ARE DISPOSED ON A FRONTSIDE SURFACE
220
DIRECTING HIGH-KINETIC-ENERGY LIGHT ELEMENT ATOMS TOWARD THE FRONTSIDE SURFACE OF THE TARGET ELECTRODE

FIG. 2

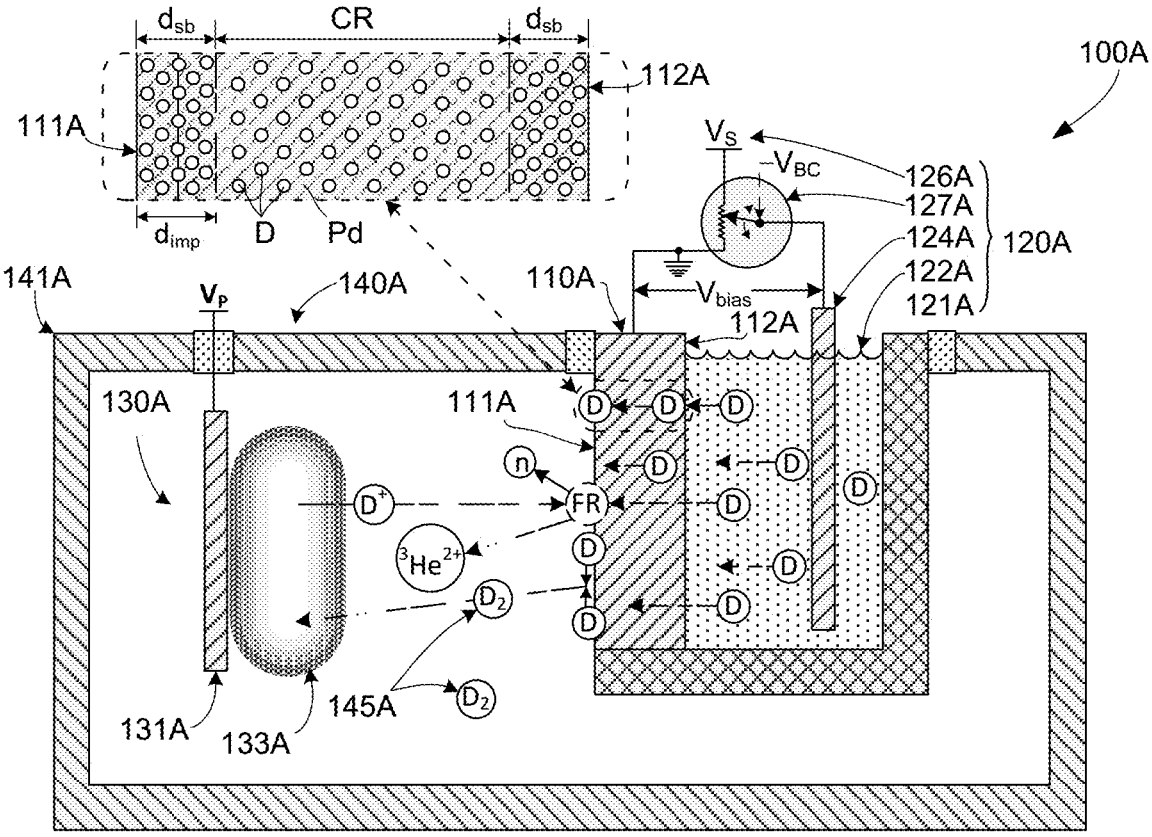

d_{sb}
CR
d_{sb}
112A
111A
100A
V_S
V_{BC}
126A
127A
124A
122A
121A
120A
d_{imp}
D
Pd
141A
V_P
140A
110A
V_{bias}
112A
130A
111A
n
FR
$^3He^{2+}$
D_2
145A
131A
133A

FIG. 3

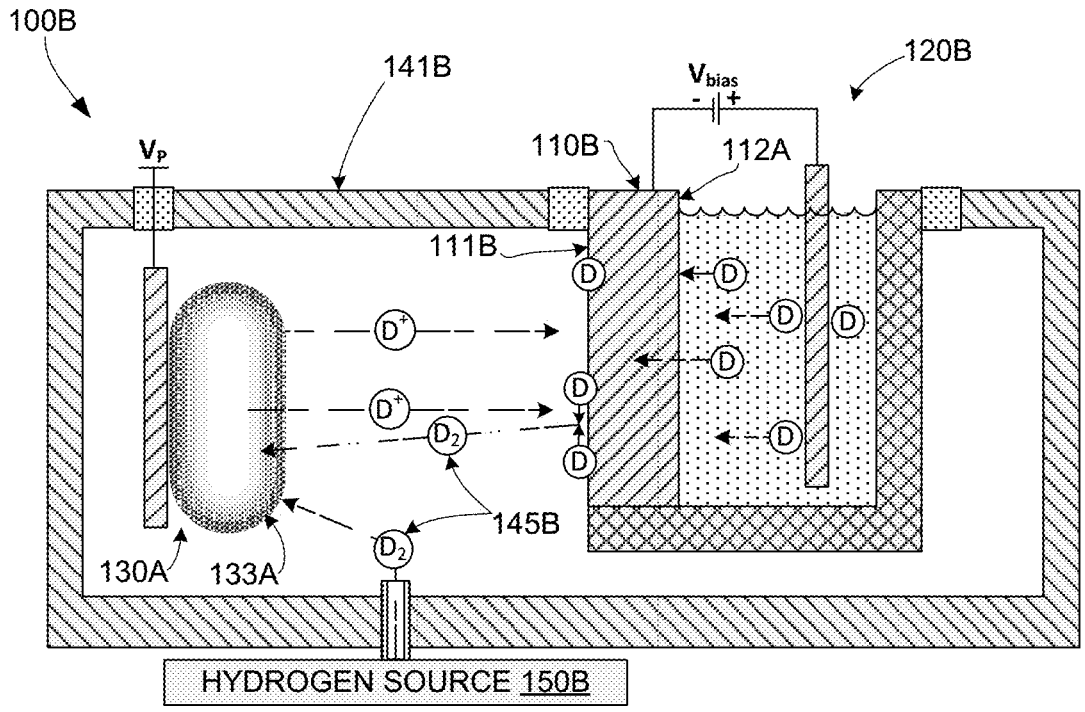

100B
141B
120B
V_{bias}
V_P
110B
112A
111B
145B
130A
133A
HYDROGEN SOURCE 150B

FIG. 4

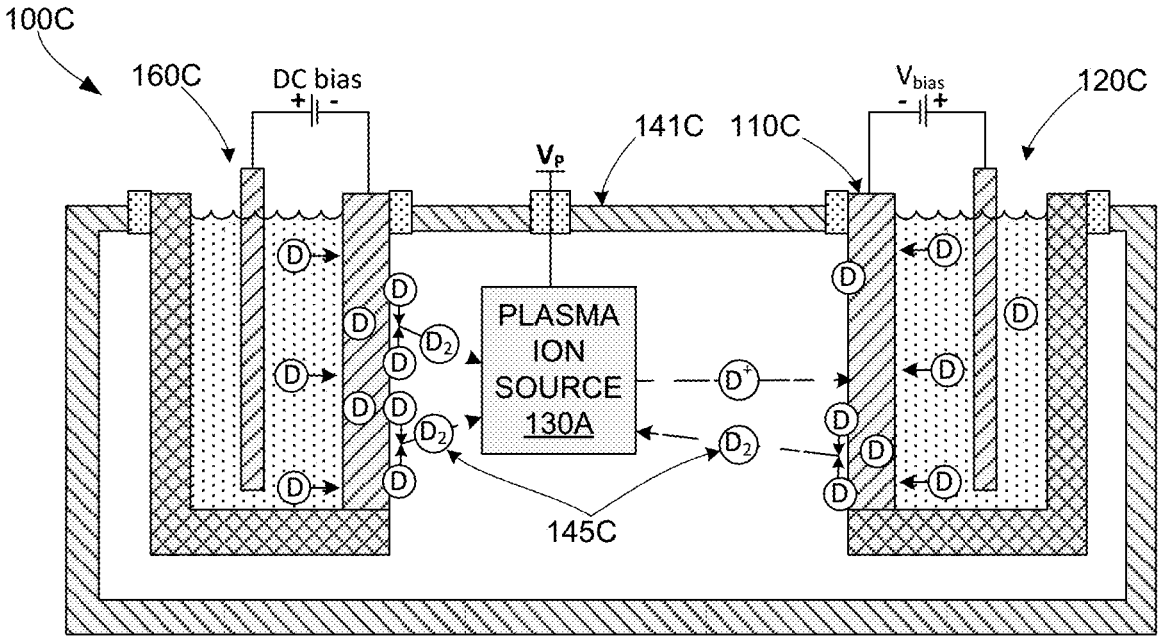

100C
160C
DC bias
+ -
V_p
141C
110C
V_{bias}
- +
120C
PLASMA
ION
SOURCE
130A
D
D_2
D^+
145C

FIG. 5

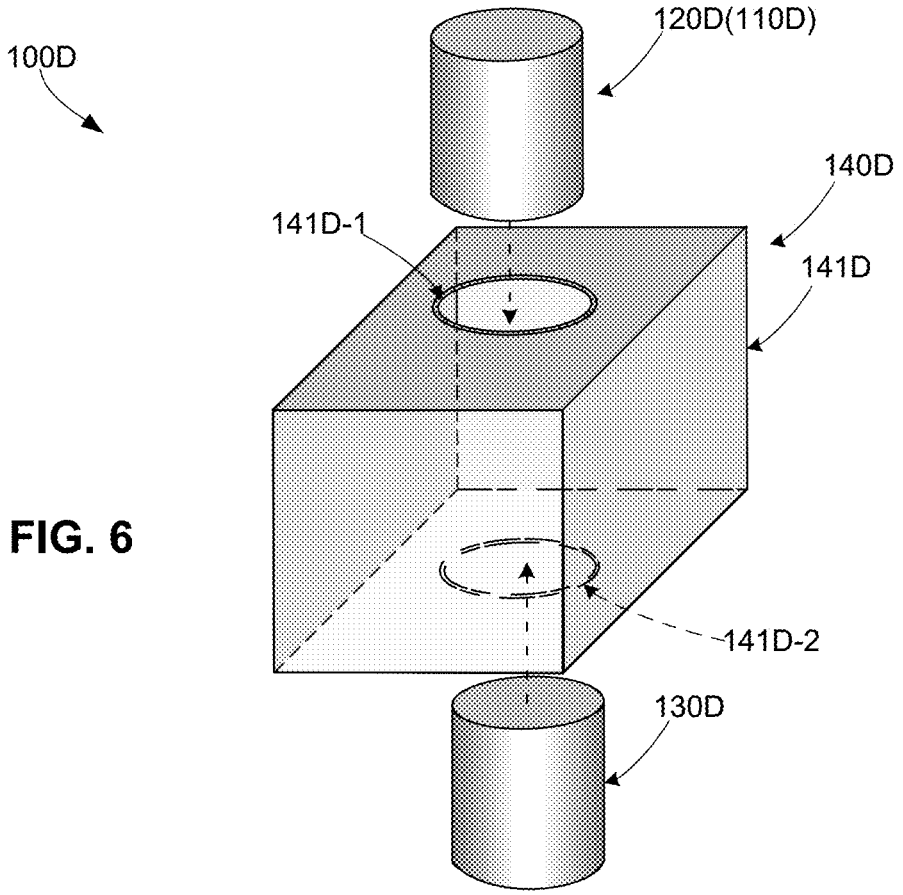

100D
120D(110D)
140D
141D-1
141D
141D-2
130D

FIG. 6

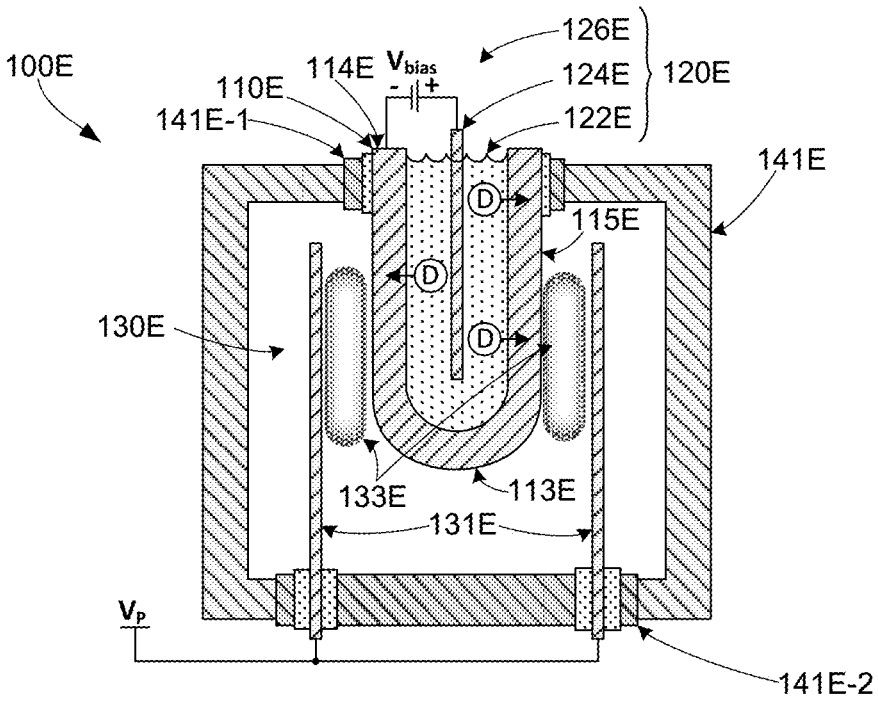

100E
126E
124E
122E
120E
114E
V_{bias}
110E
141E-1
141E
115E
D
130E
133E
113E
131E
V_P
141E-2

FIG. 7

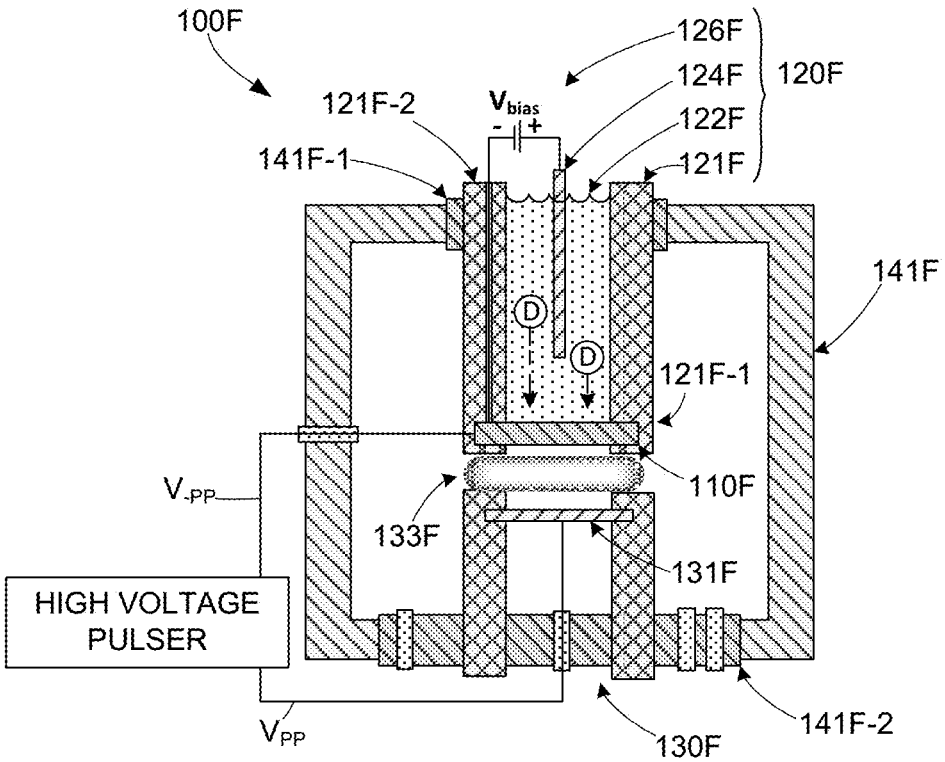

100F
126F
124F
122F
121F
120F
121F-2
V_{bias}
141F-1
141F
D
121F-1
110F
V_{-PP}
133F
131F
HIGH VOLTAGE PULSER
V_{PP}
130F
141F-2

FIG.8

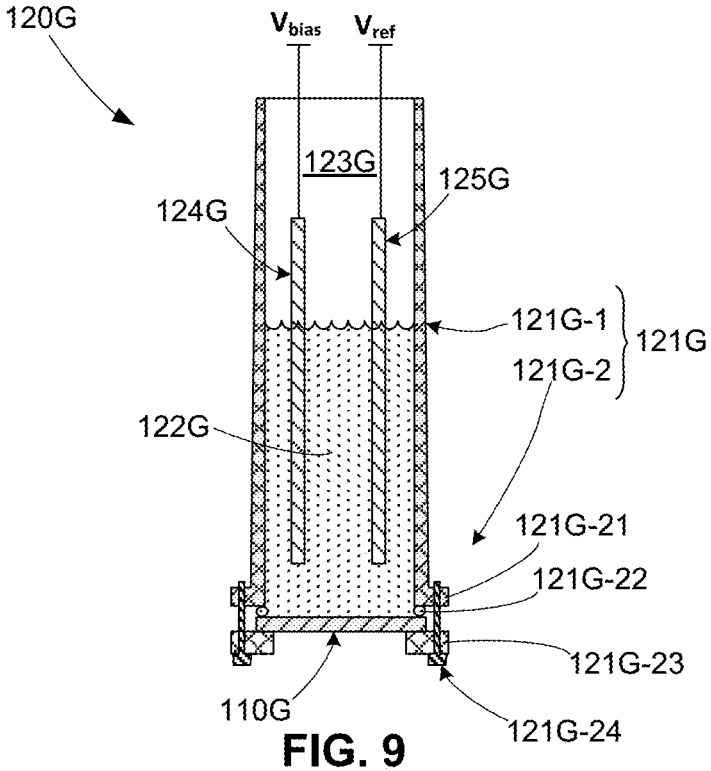

120G
V_{bias}
V_{ref}
123G
125G
124G
121G-1
121G
121G-2
122G
121G-21
121G-22
121G-23
110G
121G-24

FIG. 9

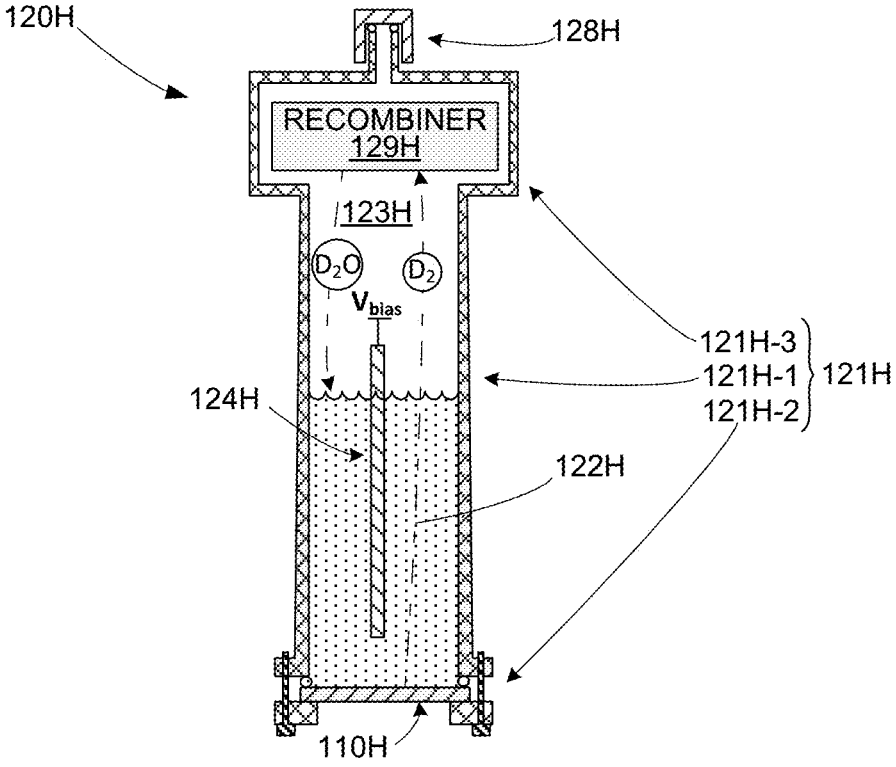

120H
128H
RECOMBINER
129H
123H
D_2O
D_2
V_{bias}
121H-3
121H-1
121H
121H-2
124H
122H
110H

FIG. 10

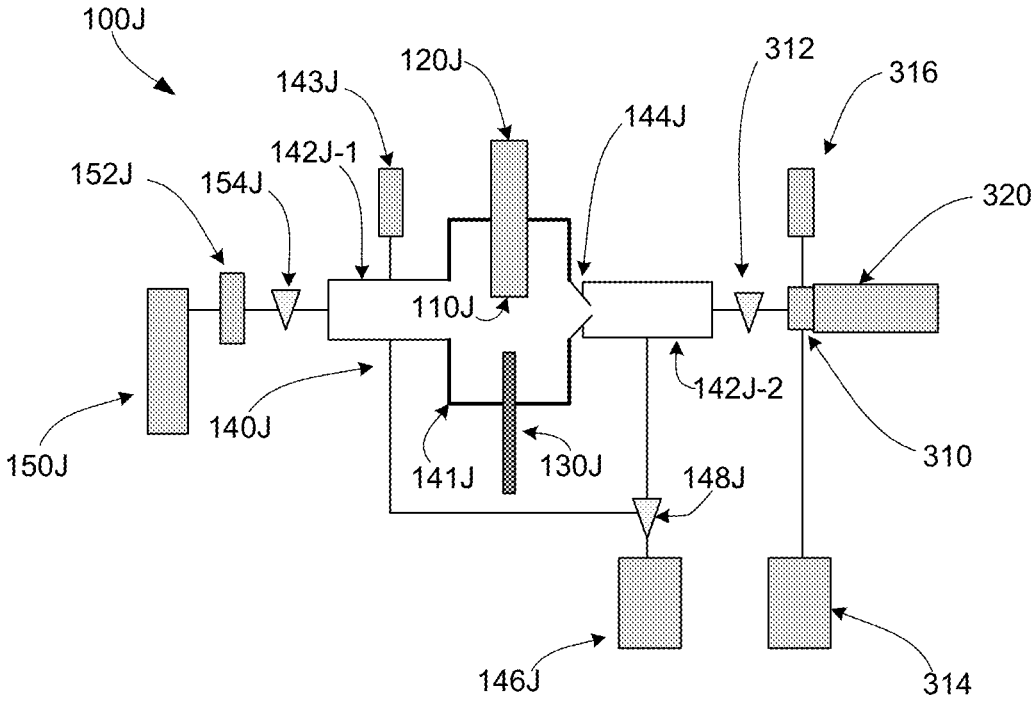


FIG. 11A

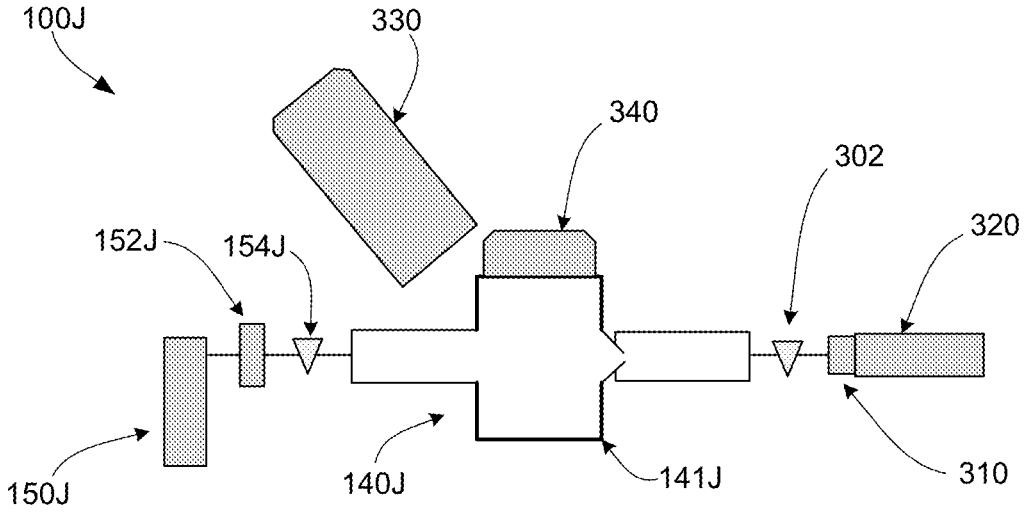


FIG. 11B

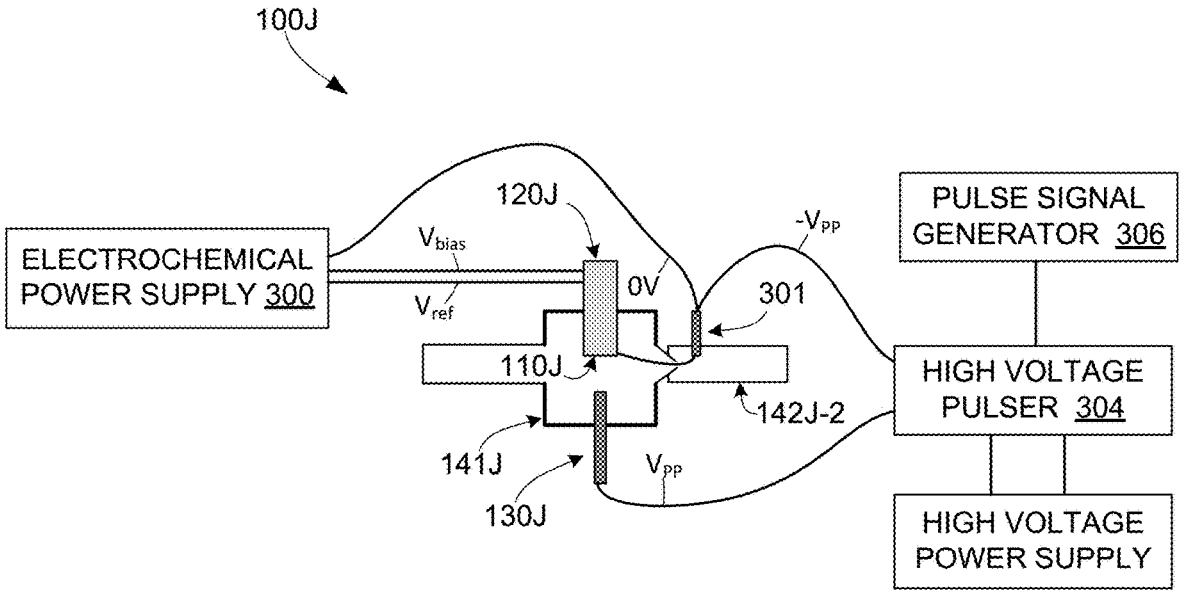


FIG. 12

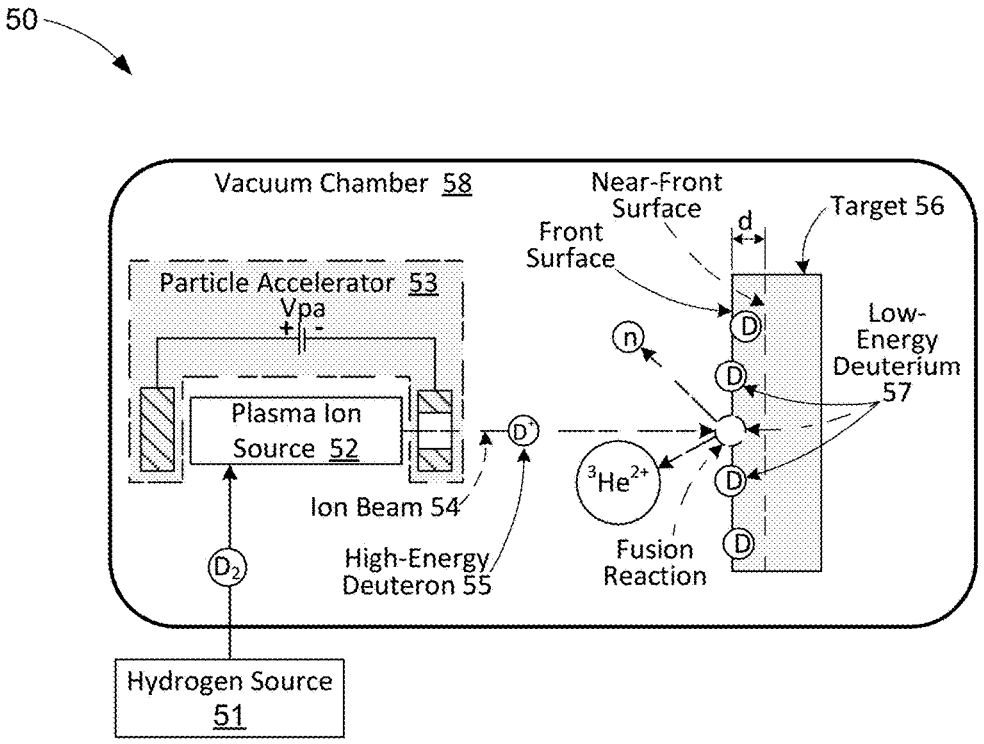


FIG. 13
(PRIOR ART)

APPARATUS AND METHOD FOR SOURCING FUSION REACTION PRODUCTS

RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional patent application 62/937,716, entitled "APPARATUS AND METHOD FOR SOURCING FUSION REACTION PRODUCTS", which was filed on Nov. 19, 2019, and is incorporated by reference herein.

STATEMENT OF GOVERNMENT SUPPORT

[0002] This invention was made with government support under Contract No. DE-AC02-05CH11231 awarded by the U.S. Department of Energy. The government has certain rights in this invention.

FIELD OF THE INVENTION

[0003] This invention relates to nuclear reactions, and more particularly to apparatus/methods for sourcing neutrons and other fusion reaction products.

BACKGROUND OF THE INVENTION

[0004] Small-scale neutron generators are used by universities and laboratories to conduct various forms of research in several branches of science (e.g., physics, chemistry, biology, engineering and medicine), and more recently in the study of hydrogen fusion reactions as part of the quest for utilizing nuclear fusion as an energy source and in nuclear astrophysics, particularly the effects of electron screening on fusion yields. As used herein, the phrase "neutron source" broadly refers to any device that emits neutrons, irrespective of the fission-based or fusion-based mechanism utilized to generate the neutrons, whereas the phrase "neutron generator" refers to a class of neutron source devices that utilize fusion-based mechanisms, and more particularly to devices that involve the fusion of at least one hydrogen isotope (e.g., the fusion of one deuterium or one tritium nucleus and a deuterium nucleus, or the fusion of a proton (^{1}H) and a boron nucleus). The small-scale neutron generators typically used for research purposes produce neutrons (and other fusion reaction products) by colliding together hydrogen isotope atoms (i.e., deuterium and/or tritium). As described below with reference to FIG. **13**, a vacuum chamber and other bulky equipment are required to facilitate this fusion-based mechanism. In contrast, small-scale fission-based neutron sources typically generate neutrons using radioactive source materials (e.g., the spontaneous decay of unstable isotopes such as californium-252), thereby avoiding the bulky equipment needed by small-scale neutron generators. However, the storage and maintenance of unstable isotopes presents several cost, safety, shelf-life and security issues that complicate the use of small-scale fission-based neutron sources. Neutron generators are therefore preferred over fission-based neutron sources for general safety reasons (i.e., because hydrogen isotope sources are relatively stable and non-radioactive), and because of the high cost associated with storing and maintaining radioactive source materials.

[0005] FIG. **13** depicts a simplified conventional neutron generator **50** of the type currently utilized in many research facilities. Hydrogen isotope particles (e.g., deuterium gas molecules D_2 and/or tritium gas molecules) are fed from a hydrogen source **51** (e.g., a hydrogen gas supply or a hydrogen getter material) to a plasma ion source **52** for ionization. Plasma ion source **52** may be operably positioned relative to a linear particle accelerator **53** that produces an ion beam **54** by accelerating and directing the ionized hydrogen isotope ions **55** (e.g., deuterons D^+ and/or tritons) toward the front surface of a target **56**. Target **56** is typically a hydrogen absorbing material that is pre-loaded with hydrogen isotope atoms **57** (e.g., substantially stationary deuterium atoms D), and/or may be loaded by hydrogen isotope atoms that are transmitted in ion beam **54** and captured in the hydrogen absorbing material. To minimize the chance of unwanted collisions with random gas molecules, plasma ion source **52** and target **56** are housed in a vacuum chamber **58** that is maintained at a near-vacuum pressure level (e.g., less than 10 Torr). With this arrangement, fusion reactions occur when the path of a high-energy ionized hydrogen isotope atom **55** intersects the fusion cross section of a hydrogen isotope atom **57** and the high-energy hydrogen isotope atom nucleus has enough kinetic energy to tunnel through or overcome the Coulomb repulsion barrier between the two isotopes' positively charged nuclei, whereby the high-energy hydrogen isotope atom nucleus fuses with the nucleus of the hydrogen isotope atom in target **56**. As depicted in FIG. **13**, the fusion reaction products generated by such fusion reactions involving a high-energy deuteron **55** and a low-energy deuterium atom **57** include an He-3 atom/ion (e.g., $^3He^{2+}$) and a neutron (n) having a kinetic energy of approximately 2.5 MeV.

[0006] Current problems associated with the use of conventional small-scale neutron generators include their ability to control neutron production rates (i.e., the rate at which fusion reactions occur) and to deliver neutron rates at low cost in a compact setup for extended periods of time (i.e., greater than 1,000 hours). There are tradeoffs between size, weight and power and neutron rates for specific applications (e.g., stationary vs. portable neutron generators). As explained above, each deuteron-deuterium fusion reaction requires the nucleus of a high-energy deuteron **55** to collide precisely with the nucleus of a deuterium atom **57**. The rate of neutron production is generally proportional both to the rate at which high-energy deuterons **55** are transmitted in ion beam **54** (i.e., the ion current) and to the number of deuterium atoms **57** that are within an effective penetration depth d of the target's front surface. That is, each high-energy deuteron **55** loses kinetic energy upon entering the front surface of target **56**, and its kinetic energy gradually decreases in proportion to its penetration depth, so its effective penetration depth d (i.e., the penetration depth within which the deuteron retains enough kinetic energy to fuse with a deuterium atom **57**) is determined by its kinetic energy. In order to achieve high neutron production rates, commercial neutron generators typically generate deuterons **55** with kinetic energies of about 80 keV, which corresponds to an effective penetration depth of about 100 nm (i.e., collisions with deuterium atoms **57** disposed within about 100 nm of the front surface's terminating atom layer typically generate fusion reactions, but collisions occurring at depths greater than about 100 nm do not). During operation, the rate of neutron production is typically relatively high when target **56** is freshly pre-loaded due to the high number of deuterium atoms **57** present on the near-front surface region of target **56** at the start of a neutron production session. However, the number of deuterium atoms **57** within the effective penetration depth region (i.e., on the near-front surface) of target **56** depends on a balance between the rate

at which deuterium atoms are added to target **56** by way of beam-loading (discussed below) and the rate at which deuterium atoms are lost from target **56** due to desorption, sputtering and out-diffusion, as well as fusion reactions. A gradual decrease over time in the number of deuterium atoms **57** on the near-front surface of target **56** leads to gradually decreasing rates of nuclear fusion reactions and, hence, gradually decreasing neutron generation rates.

[0007] A conventional technique for maintaining desired nuclear fusion reaction rates involves "beam loading" deuterium atoms **57** into the near-front surface region of target **56** by gradually increasing the flux of high-energy deuterons **55** transmitted in ion beam **54**, thereby replenishing at least some of the low-energy deuterium atoms that desorb or are otherwise removed from target **56**. That is, some high-energy deuterons **55** that are transmitted by ion beam **54** onto the front target surface become captured in the target material, whereby these captured ions are effectively converted into low-energy deuterium atoms **57**. The beam loading technique facilitates nominal nuclear reaction rate control by gradually increasing the amount of hydrogen isotope atoms supplied to plasma ion source **52** and/or increasing the voltage level of particle accelerator source Vpa in order to gradually increase the flux of high-energy deuterons **55** transmitted in beam **54**, thereby increasing the number of ions that become captured (loaded) into the front target surface. Unfortunately, the beam loading technique often fails to fully replenish the low-energy deuterium atoms that are lost from the target's front surface, whereby the rate of nuclear fusion reactions (and, hence, neutron generation) typically declines over time.

[0008] What is needed is an apparatus/method for sourcing neutrons that addresses the above-mentioned problems associated with conventional neutron sourcing approaches. More specifically, what is needed is a compact, low-cost fusion-based neutron source capable of producing neutrons at a more controllable rate and for a longer period than that achievable using conventional neutron generators and associated techniques.

SUMMARY OF THE INVENTION

[0009] The present invention is directed to an apparatus and improved method for sourcing fusion reaction products (e.g., neutrons and helium atoms or other atomic particles) that utilizes an electrochemical loading process to load low-kinetic-energy (low-k) light element particles into a light-element-absorbing target electrode while directing high-kinetic-energy (high-k) light element particles onto the target electrode. In one embodiment the electrochemical loading process is achieved using an electrochemical cell that is configured to maintain contact between an electrolyte solution and a surface of the target electrode while an electrochemical bias (i.e., either a bias voltage or bias current) is applied to the electrolyte solution such that low-k light element particles are continuously absorbed from the electrolyte solution into the target electrode. Once absorbed, the low-k light element particles diffuse throughout the light-element-absorbing material, thereby loading the target electrode with low-k light element particles. A particle accelerator (e.g., an ion source or plasma ion source) is utilized to accelerate and direct high-k light element particles against the target electrode, with each high-k light element particle having sufficient energy to generate a fusion reaction when it operably collides with an associated low-k light element particle disposed on or in the target electrode. By utilizing the electrochemical loading process to continuously replenish the low-k light element particles that exit the target electrode (i.e., by way of desorbing out of the target electrode or by being fused with associated high-k light element particles), the present invention facilitates substantially longer uninterrupted fusion-reaction-product sourcing operations than those achievable by conventional apparatuses and approaches. Moreover, the electrochemical loading process requires only a small bias voltage/current to maximize the number of absorbed low-k light element particles in the target electrode while facilitating a substantial reduction in the power required to accelerate the high-k light element particles, whereby the apparatus requires substantially less power (i.e., in comparison to conventional beam loading approaches) to achieve high nuclear reaction product sourcing rates.

[0010] In some embodiments the target electrode comprises a thin layer of electrically conductive light-element-absorbing material (e.g., a metal foil having a thickness in the range of 0.1 mm to 1 mm), with high-k light element particles being directed onto a frontside (first) surface of the target electrode while the electrochemical loading process is performed through the opposing backside (second) surface of the target electrode. This backside-to-frontside diffusion arrangement achieves high nuclear fusion reaction rates by efficiently and continuously sourcing low-k light element particles to large target electrode frontside surface regions while simultaneously directing high-k light element particles against the frontside surface. That is, by forming the target electrode using an electrically conductive material and applying the electrochemical bias (i.e., either a bias voltage or bias current) between the electrolyte solution the target electrode while the electrolyte solution contacts the entire backside target electrode surface, low-k light-element particles are driven from the electrolyte solution to the target electrode and absorbed through the entire surface area of the backside surface. By further forming the target electrode as a thin plate (e.g., wafer or cylindrical wall-like structure) of light-element-absorbing material, each absorbed low-k light element particle is then required to diffuse a minimal distance from its absorption point on the backside surface to an opposing point on the wall-like frontside surface, whereby the backside-to-frontside diffusion arrangement minimizes the time required to effectively load the target electrode with low-k light element particle. In addition, by way of utilizing a plasma ion source or other particle accelerator capable of directing high-k light element particles onto the entire wall-like frontside surface, the backside-to-frontside diffusion arrangement further facilitates efficient fusion reaction product sourcing operations by maximizing the number of potential collisions between high-k and low-k light element particles. In addition, the liquid/solid contact between the electrolyte solution and the target's backside surface enables higher neutron production rates by facilitating the efficient transfer of heat from the target electrode to the electrolyte solution. That is, the target's frontside surface temperature varies in proportion to the ion power/flux (i.e., the rate of high-k light element particles directed against the frontside surface), and the rate of desorption of low-k light element particle from the frontside surface varies in proportion to the frontside surface temperature. By utilizing the liquid/solid heat transfer mechanism to draw heat away from frontside surface, the present invention achieves lower frontside sur-

face temperatures for a given ion beam power/flux level than is achievable using conventional methods, thereby facilitating higher neutron production rates by reducing the desorption rate of low-k light element particle from the target's frontside surface.

[0011] In some embodiments the electrochemical cell includes an electrochemical anode that is immersed in or otherwise operably contacts the electrolyte solution and is coupled to a bias source to apply the electrochemical bias (i.e., either a bias voltage or a bias current) between the target electrode and the electrochemical anode. Note that, in this arrangement, the target electrode effectively forms an electrochemical cathode of the electrochemical cell. By forming the target electrode using a material that is both electrically conductive and light-element-absorbing (e.g., hydrogen permeable) and by configuring the electrochemical anode to optimize the generated bias force, a small (e.g., few volts) applied bias voltage or bias current is sufficient to initiate the electrochemical loading process by efficiently driving low-k light element particles from the electrolyte solution to the target electrode's backside surface such that the low-k light element particles then diffuse through the target electrode to the opposing frontside (first) surface, thereby enhancing the fusion reaction process by continuously refreshing the supply of low-k light element particles disposed on the frontside (first) surface. Further, the inventors bel the rate of fusion reactions (e.g., the rate of neutron generation) varies (i.e., increases or decreases) in direct proportion to corresponding variances in diffusion rate of low-k light element particles through the target electrode, and that the diffusion rate varies in proportion to corresponding variances the applied bias level. Accordingly, in one embodiment the electrochemical cell further includes a bias control device configured to facilitate user-controllable adjustments to the electrochemical bias's voltage/current level by way of an externally applied bias control signal, thereby providing a novel technique for controlling the rate of fusion reactions generated by a host fusion reaction product sourcing apparatus that represents a substantial improvement over the fusion reaction rate control achievable using conventional beam loading techniques.

[0012] In presently preferred embodiments the apparatus is configured for nuclear reactions involving hydrogen isotopes (e.g., deuterium and/or tritium). In some practical embodiments, the low-k light element particles are deuterium atoms supplied from a suitable electrolyte solution (e.g., aqueous sulfuric acid in heavy water), the high-k light element particles are deuterons, the target electrode comprises a metal foil comprising palladium and having a thickness in the range of 0.1 mm to 1 mm. In other embodiments the Pd foil may be configured to function both as a target electrode that absorbs/diffuses tritium particles from a tritium-based electrolyte solution, and also as a filter that prevents the diffusion of contaminant ^{3}He atoms, which naturally arise due to T decay, from entering the vacuum chamber. In alternative embodiments the target electrode may be a lithium absorbing material (e.g., $LiCoO_4$) and the low-k light element atoms comprise lithium isotope atoms—when bombarded with energetic protons, the lithium containing target electrode could prove useful for the study of an astrophysical process known as lithium burning. In such an application, the electrochemical anode would likely comprise graphite or silicon.

[0013] In some embodiments the particle accelerator and at least a portion of the target electrode that includes frontside surface are maintained by a vacuum system in a low-pressure (e.g., approximately 10 Torr or less) rarified atmosphere including light element gas molecules (e.g., D_2 and/or T_2). In some embodiments the electrochemical cell includes a housing structure that forms a vacuum-tight seal around the target electrode such that the frontside surface is exposed to the low-pressure rarified atmosphere and the backside surface and electrolyte solution are subjected to substantially atmospheric pressures (i.e., approximately 760 Torr). In some embodiments the particle accelerator is implemented using a plasma ion source having a counter electrode configured to produce a glow plasma discharge, which may also be an electrically pulsed plasma discharge, between the counter electrode and the target electrode. When implemented within the low-pressure rarefied atmosphere, the plasma discharge ionizes the light element gas molecules, and accelerates the resulting dissociated ions to provide the high-k light element particles directed toward the first surface of the target electrode. An advantage provided by this arrangement is that the requisite light element gas molecules may be entirely supplied by low-k light element particles that have diffused entirely through the target electrode and detached from the frontside surface into the vacuum chamber, which facilitates substantially reducing the overall size and cost of a nuclear generator unit in some embodiments by way of eliminating the need for an expensive and bulky hydrogen source (e.g., a gas bottle or getters). In addition, the density of the electrolyte solution is over 1000 denser than hydrogen gas and a few ml of the electrolyte solution can contain more hydrogen atoms than in present in a gas cylinder (few liter volume), as well as more hydrogen atoms than present in a hydrogen get compound (commonly used to provide hydrogen isotopes for sealed neutron generators). Hence the electro-chemical solution provides a much more compact and low-cost source of hydrogen isotopes. In other embodiments the supply of requisite light element gas generated by the targeted (first) electrochemical cell may be supplemented using conventional techniques (e.g., supplying D_2 and/or T_2 gas from a hydrogen gas bottle or hydrogen getters), or may be supplemented using a non-targeted (second) electrochemical cell that is configured to supply light element gas molecules using the same process utilized by the targeted electrochemical cell.

[0014] In some exemplary practical embodiments the apparatus is configured such that the target electrode and the electrochemical cell are inserted through an upper flange into a primary vacuum chamber, and the plasma ion source (particle accelerator) is inserted through a lower flange into the primary vacuum chamber. In one exemplary specific embodiment the target electrode is a tube-shaped structure formed substantially entirely of light-element-absorbing material that contains the electrolyte solution and is mounted onto an upper flange of the vacuum chamber such that a first (e.g., closed-end) portion is disposed inside the vacuum chamber and a second (e.g., opened-end) portion is disposed outside of the vacuum chamber. In this embodiment the plasma ion source includes a cylindrical counter electrode that surrounds an outer cylindrical surface of the tube-shaped target electrode. This tube-shaped configuration potentially increases neutron generation for a given vacuum chamber size by generating a cylindrical plasma discharge

that supplies high-k light element particles to the entire outer cylindrical surface of the tube-shaped target electrode. In another exemplary embodiment the electrochemical cell includes a cylindrical housing containing electrolyte solution and the target electrode is a disk-shaped wafer that is secured to a first (closed) end portion of the cylindrical housing that is disposed inside the vacuum chamber, and the plasma ion source includes a disk-shaped counter electrode that is positioned such that a disk-shaped plasma discharge is generated between the disk-shaped counter electrode the target electrode. This disk-shaped configuration is presently considered less expensive to produce and maintain than the tube-shaped configuration. In an alternative exemplary embodiment the electrochemical cell includes both a counter electrode (electrochemical anode) and a reference electrode disposed in contact with the electrolyte solution. In another alternative exemplary embodiment the electrochemical cell utilizes a recombiner to ensure that hydrogen sourced from the electrolyte is not lost due to the evolution of hydrogen gas at the target electrode.

[0015] In other embodiments the apparatus includes one or more reaction product detecting systems to measure fusion reaction products for purposes of achieving possible breakthroughs in the field of nuclear fusion science. That is, fusion reaction rates are determined by the kinetic energy of the reaction partners (a kinetic energy of 1 keV equals a temperature of about 10 million degrees). Achieving energy gain from fusion requires very hot, dense and well-confined plasmas that are difficult and expensive to produce. The inventors have observed that fusion reactions at a few keV can be enhanced 100-fold when the reactions take place in metals, as compared to reactions taking place in gas phase. Preliminary experimental results generated by the methods and system described above (i.e. where fusion reactions occur in a metal such as palladium) indicate possibly significant changes to the presently understood branching ratio of deuterium-deuterium fusion reactions, indicating the discovery of potentially new nuclear processes. If these preliminary experimental results are confirmed and the underlying mechanisms of these new nuclear processes can be understood, then implementation of the present invention could lead to fusion energy without the need for very hot plasmas (i.e., without fulfilling the Lawson criteria), thereby providing a path to low cost, carbon free electricity. Accordingly, any of the various apparatus configurations mentioned above may be further enhanced to facilitate the potential discovery of significant breakthroughs in the field of nuclear fusion science by way of including one or more reaction product detecting systems (e.g., at least one of a residual gas analyzer, a mass spectrometer, a neutron detector, a charged particle detector and a gamma ray detector that is/are operably configured to detect fusion reaction products generated by fusion reactions occurring in the target electrode). In addition, the invention can support the path to fusion power with hot, dense and well-confined plasmas by providing a technique for low cost tritium recovery and purification.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] These and other features, aspects and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings, where:

[0017] FIG. **1** is a cross-sectional side view showing a simplified generalized apparatus for sourcing nuclear fusion products according to a generalized embodiment of the present invention;

[0018] FIG. **2** is a flow diagram depicting a generalized method for sourcing nuclear fusion products according to an embodiment of the present invention;

[0019] FIG. **3** is a cross-sectional side view showing a simplified apparatus for sourcing nuclear fusion products according to a specific embodiment of the present invention;

[0020] FIG. **4** is a cross-sectional side view showing a simplified apparatus for sourcing nuclear fusion products according to a specific embodiment of the present invention;

[0021] FIG. **5** is a cross-sectional side view showing a simplified apparatus for sourcing nuclear fusion products according to yet another specific embodiment of the present invention;

[0022] FIG. **6** is a perspective view showing a simplified apparatus for sourcing nuclear fusion products according to yet another specific embodiment of the present invention;

[0023] FIG. **7** is a cross-sectional side view showing a simplified apparatus for sourcing nuclear fusion products according to a specific embodiment of the present invention;

[0024] FIG. **8** is a cross-sectional side view showing a simplified apparatus for sourcing nuclear fusion products according to a specific embodiment of the present invention;

[0025] FIG. **9** is a cross-sectional side view showing a electrochemical cell of an apparatus for sourcing nuclear fusion products according to another specific embodiment of the present invention;

[0026] FIG. **10** is a cross-sectional side view showing a electrochemical cell of an apparatus for sourcing nuclear fusion products according to yet another specific embodiment of the present invention;

[0027] FIGS. **11**A and **11**B are simplified front and top schematic views, respectively, showing an apparatus for sourcing nuclear fusion products according to yet another specific embodiment of the present invention;

[0028] FIG. **12** is a simplified wiring diagram depicting electrical connections utilized by the apparatus of FIGS. **11**A and **11**B; and

[0029] FIG. **13** is a cross-sectional side view showing a generalized conventional neutron generator.

DETAILED DESCRIPTION OF THE DRAWINGS

[0030] The present invention relates to an improvement in methods and apparatus/systems for sourcing nuclear fusion products. The following description is presented to enable one of ordinary skill in the art to make and use the invention as provided in the context of a particular application and its requirements. As used herein, directional terms such as "downward", "front", "back", "frontside", "backside", "upper" and "lower" are intended to provide relative positions for purposes of description and are not intended to designate an absolute frame of reference. Various modifications to the preferred embodiment will be apparent to those with skill in the art, and the general principles defined herein may be applied to other embodiments. Therefore, the present invention is not intended to be limited to the embodiments shown and described but is to be accorded the widest scope consistent with the principles and novel features herein disclosed.

[0031] FIG. **1** depicts a simplified and generalized fusion reaction product sourcing apparatus **100**, and FIG. **2** is a

simplified flow diagram showing a generalized method **200** for sourcing nuclear fusion products. As indicated in FIG. **1**, generalized fusion reaction product sourcing apparatus **100** includes a target electrode **110**, an electrochemical cell **120** and a particle accelerator **130**. Although method **200** is described below with reference to operations performed using apparatus **100**, it is understood that the associated methodology is not necessarily restricted to operations performed by the specific structures of apparatus **100**.

[0032] Referring to FIG. **1**, target electrode **110** is characterized by being formed of a material that is light-element-absorbent (i.e., receptive and permeable to atoms of one or more target light elements) and preferably electrically conductive. For example, in practical embodiments described below, hydrogen isotope (e.g., deuterium and/or tritium) ions and atoms are designated light element particles, and target electrode **110** comprises palladium (Pd), which is hydrogen permeable and also electrically conductive, and is therefore light-element-absorbing with respect to the designated light element particles (i.e., D and T). In other embodiments the light element may be selected from the group of boron, beryllium, or lithium, or a hydride of a light element (e.g., lithium hydride), in which case the target electrode **110** may comprise a suitable material that exhibits permeability to the atoms of the selected light element. In some embodiments, electrode **110** is a thin wafer or plate-like structure having a frontside (first) surface **111** that faces away from electrochemical cell **120** and toward particle accelerator **130**, and a backside (second) surface **112** that faces toward at least a portion of electrochemical cell **120**. Note that the structural dimensions depicted in the figures are intentionally and significantly distorted for illustrative purposes. For example, a thickness dimension T of electrode **110** may be substantially smaller (i.e., relative to its lateral dimensions) than that depicted in the figures. in other embodiments electrode **110** may be a solid (e.g., block-like) structure.

[0033] The present invention is described herein with reference to certain generalized phrases that are used for brevity and convenience. For example, the description references fusion reactions involving collisions between two "light element particles" that occur "on a frontside surface" (e.g., frontside surface **111** of target electrode **110**). In the context of a given fusion reaction, the phrase "light element particle" refers to the colliding light element atoms or ions (e.g., a deuteron colliding with a deuterium atom), and the phrase "on a frontside surface" is intended to mean a location that is either on the outermost layer of atoms that technically define the corresponding surface, or a near-surface location that within a distance of approximately 100 nm from the outermost atomic layer. In other contexts, the phrase "light element particle" may refer to such light element atoms or ions as part of a larger molecule (e.g., light element particles LL disposed in electrolyte solution **122** may be part of a polyatomic ion such as hydronium (H30+) or ammonium (NH_4^+)).

[0034] Referring to FIG. **2**, method **200** includes electrochemically loading low-kinetic-energy (low-k) light element particles into a target electrode such that some of the low-k light element particles are disposed on a frontside surface of the target electrode (block **210**). Referring to the right side of FIG. **1**, this electrochemical loading process is performed by apparatus **100** using an electrochemical cell **120** including an electrolyte solution **122** and a bias voltage source **126** that is configured to apply a bias voltage (electrochemical bias) V_{bias} to electrolyte solution **122**. Electrolyte solution **122** is a liquid-state substance including low-kinetic-energy (low-k) light element particles LL that is contained or otherwise disposed such that electrolyte solution **122** contacts backside surface **112** of target electrode **110**. For example, when the designated light element is deuterium, electrolyte solution **122** may comprise an electrolyte containing hydrogen such as aqueous D_2SO_4 in D_2O. Electrochemical bias source **126** applies bias voltage (potential) V_{bias} to electrolyte solution **122** in order to drive low-k light element particles LL disposed in electrolyte solution **122** to backside surface **112**, thereby causing these driven low-k light element particles to be absorbed into target electrode **110**. In some embodiments target electrode **110** functions as the cathode of electrochemical cell **120** (i.e., anode **124** is biased positive relative to target electrode **110**). The absorbed low-k light element particles diffuse (migrate) through target electrode **110** from backside surface **112** and become disposed on frontside surface **111**. In this way, low-k light element particles LL are continuously sourced to frontside surface **111** while anode is biased positive relative to target electrode **110**.

[0035] Referring again to FIG. **2**, method **200** also includes directing high-kinetic-energy (high-k) light element particles toward the target electrode (block **220**). Referring to the left side of FIG. **1**, this high-k directing process is performed using particle accelerator **130**, which utilizes known techniques to accelerate and direct high-k light element particles HL toward frontside surface **111** of target electrode **110** with sufficient energy to produce fusion reactions (FR) whenever a given high-k light element particle HL operably collides with an associated low-k light element particle LL disposed on frontside surface **111**. That is, particle accelerator **130** functions to accelerate light element particles (e.g., deuterons) to a suitable energy level (i.e., approximately 1 kV or higher), with the accelerating force being applied in a direction that causes the high-k light element particles HL to strike frontside surface **111**. An operable collision occurs when the path of a high-k light element particle HL intersects the fusion cross section of an associated low-k light element particle LL that is disposed on frontside surface **111**, and the kinetic energy of the high-k light element particle HL is sufficient for its nucleus to tunnel through (or to overcome) the Coulomb repulsion barrier between the two isotope's positively charged nuclei, whereby the nucleus of high-k light element particle HL fuses with the nucleus of low-k light element particle LL. These operable collisions generate fusion reactions FR that produce neutrons (n) and other particles (P) as fusion reaction products.

[0036] FIG. **3** depicts an apparatus **100**A including a target electrode **110**A, an electrochemical cell **120**A and an ion source (particle accelerator) **130**A that are configured and function in the manner described above with reference to FIG. **1**. As set forth below, apparatus **100**A includes several additional structures and features that facilitate fusion reactions involving the hydrogen isotopes deuterium and tritium. While these structures and features are mainly described with specific reference to deuterium-deuterium fusion reactions, these structures and features may also beneficially enhance operations involving other fusion reaction types (e.g., proton-Boron). In addition, those skilled in the art will

recognize that the structures and features described with reference to FIG. **3** may be implemented in any embodiment described herein.

[0037] This invention comprises an electrochemical cell comprising an electrochemical anode, an electrochemical reference electrode, an electrolyte containing hydrogen such as aqueous D_2SO_4 in D2O, and a hydrogen permeable cathode such as a palladium foil (between 0.1 and 1 mm thick). A controllable electrochemical potential bias between the electrochemical anode and the cathode (anode biased positive relative to the cathode) leads to the entry of hydrogen from the electrolyte into the cathode at a first cathode surface corresponding to the interface between the electrolyte and the cathode. Once absorbed at the first cathode surface, hydrogen diffuses throughout the thickness of the cathode and reaches a second cathode surface within a vacuum chamber. Hydrogen at and near (within approximately 100 nm) the second cathode surface serves as a target for bombardment with energetic light elements to produce fusion reactions.

[0038] According to a presently preferred embodiment, apparatus **100**A is implemented using deuterium (D) as the designated light element (e.g., where electrolyte solution **122**A is aqueous D_2SO_4 in D_2O), and target electrode **110**A is implemented using a palladium foil structure having a thickness in the range of 0.1 mm to 1 mm. Using these parameters, a previously unrecognized feature that led to the present invention is the similarity of two critical length scales underlying the physical process that takes place on frontside surface **111**A, where D-D fusion reactions FR occur. Referring to the dashed-box section near the top of FIG. **3**, these two length scales include an effective implantation depth d_{imp} of high-k deuterons D^+ that impinge on frontside surface **111**A, and a strong-binding depth d_{sb} inside the outermost atomic layers of a Pd foil in which deuterium atoms D are relatively densely packed. The effective implantation depth d_{imp} represents an average depth that a high-k deuterium particles can penetrate into the Pd foil while retaining sufficient energy to generate a fusion reaction, and is on the order of 1 nm to 10 nm for deuterons with kinetic energy on the order of 1 kV in palladium (i.e., high-k deuterium particles that penetrate beyond this depth typically lose too much kinetic energy to fuse with a low-k deuterium particle). The strong-binding depth d_{sb} defines a layer/region near frontside surface **111**A and backside surface **112**A within which the density of deuterium atoms is relatively high, as compared with a lower density of deuterium atoms disposed in an intervening central region CR. That is, low-k deuterium particles are relatively densely packed immediately after being absorbed through backside surface **112**A, then become less densely packed as they diffuse from backside surface **112**A toward frontside surface **111**A, and then become more densely packed as they move within strong-binding depth d_{sb} of frontside surface **111**A. The strong-binding depth d_{sb} for a palladium-foil-type target electrode **110**A is on the order of several atomic layers, which is coincidentally on same order (1 nm to 10 nm) as implantation depth d_{imp} for deuterium ions with kinetic energy of 1 keV in Pd. This means that the use of a palladium target electrode in conjunction with the electrochemical loading process of the present invention provides a continuously replenishment of high-density deuterium particles precisely where they are needed to maximize the probability of achieving high fusion reaction rates using deuterium ions with kinetic energy of 1 keV. That is, the present inventors recognized that the tendency for hydrogen isotopes to absorb preferentially at the surface of palladium (and other metals) could be exploited in this invention to create a hydrogen rich target surface that is continuously replenished by the electrochemical process, thereby facilitating substantially higher (i.e., 100×) neutron generation rates using deuterons having kinetic energies of 1 keV. Of course, this enhanced neutron generation rate may be increased by way of configuring particle accelerator **130**A to accelerate incident deuterons to higher kinetic energies, thereby increasing the effective penetration depth region to include both the high-density deuterium atoms located within strong-binding depth d_{sb} and lower density deuterium atoms located further from frontside surface **111**A. For example, utilizing deuterons with kinetic energies of 80 keV yield over a million times higher neutron generation rates than those generated by 1 keV deuterons (i.e., by increasing the effective penetration depth to 100 nm). Referring to the right side of FIG. **3**, electrochemical cell **120**A includes a containment housing **121**A that maintains electrolyte solution **122**A in contact with a backside surface **112**A, and an electrochemical anode (counter electrode) **124**A that applies an electrochemical bias (i.e., either a small b_{ias} voltage V_{bias} on the order of one to five volts, or a comparable bias current) between target electrode **110**A and electrochemical anode **124**A such that low-k deuterium particles D are driven from electrolyte solution **122**A through backside surface **112**A into target electrode **110**A. In one embodiment the electrochemical cell **120**A further includes a bias control device **127**A configured to facilitate user-controllable adjustments of bias voltage V_{bias} level by way of an externally applied bias control signal V_{BC}, thereby allowing a user to control the rate of fusion reactions generated by apparatus **100**A by way of selectively varying the level bias voltage V_{bias}.

[0039] Referring to the left side of FIG. **3**, particle accelerator **130**A and at least a portion of target electrode **110**A (i.e., including frontside surface **111**A) are maintained by a vacuum system **140**A in a low-pressure (e.g., approximately 10 Torr or less) rarified atmosphere made up of light element gas molecules (e.g., D_2 and/or T_2). Electrochemical cell **120**A includes a housing structure **121**A that supports target electrode **110**A and is operably connected to a vacuum chamber **141**A of vacuum system **140**A such that frontside surface **111**A is exposed to the rarified atmosphere, and such that backside surface **112**A and electrolyte solution **122**A are subjected to substantially atmospheric pressure (i.e., approximately 760 Torr). In some embodiments, particle accelerator **130**A is implemented using a plasma ion source **130**A having a counter electrode **131**A configured to produce a glow plasma discharge **133**A, which may also be an electrically pulsed plasma discharge, between counter electrode **131**A and target electrode **110**A. When implemented within vacuum chamber **141**A, a flux of D_2 gas released from frontside surface **111**A into vacuum chamber **141**A then feeds plasma discharge **133**A, whereby electrochemical cell **120**A serves as a source of high-k deuterons. That is, plasma discharge **133**A ionizes the D_2 gas molecules released from target electrode **110**A and accelerates the resulting dissociated high-k deuterons D^+ toward frontside surface **111**A of target electrode **110**A. An advantage provided by this arrangement is that light element gas molecules **145**B (e.g., D_2) may be entirely supplied by low-k

deuterium particles sourced from electrochemical cell **120**A, which facilitates substantially reducing the overall size and cost of apparatus **100**A by way of eliminating the need for an expensive and bulky external hydrogen source.

[0040] In some embodiments that utilize low-k tritium particles (e.g., a neutron generator that utilizes the reaction $D+T \rightarrow n+{}^{4}He$), a palladium foil target electrode may also function as a filter (i.e., in addition to sourcing low-k tritium to the target electrode's frontside surface). Devices of this sort have the problem in that tritium decays naturally into ^{3}He (plus a neutrino) with a half-life of approximately twelve years, with the unwanted result that the supply of tritium gradually becomes contaminated with ^{3}He. In the existing art, neutron generators of this type may have a sealed vacuum chamber containing T_2 gas in which the accumulating ^{3}He is difficult to remove. Using the electrochemical loading process of the present invention, if the electrolyte solution includes tritium particles (e.g., a a solution of T_2SO_4 in T_2O), then ^{3}He from continuous tritium decay would collect in the electrolyte solution **122**, but would be prevented from passing through the target electrode to the vacuum chamber. This is because certain materials, such as Pd, readily support the diffusion of hydrogen; but not helium. Therefore, the ^{3}He particles stay behind in the electrolyte solution, thereby preventing contamination of the vacuum chamber. In potential embodiments such a filtered source of pure T might be utilized in a long duration space missions, or a long service life neutron generator. In addition, this filter source can be used for tritium recovery and purification in a plasma based fusion reactor and other fusion devices.

[0041] FIG. **4** shows an apparatus **100**B according to an alternative embodiment in which the supply of requisite light element gas molecules **145**B (e.g., D_2) in the rarified vacuum chamber atmosphere is supplemented using a hydrogen source **150**B (e.g., a hydrogen gas bottle or hydrogen getters). That is, an electrochemical cell **120**B and a target electrode **110**B are operably connected to a vacuum chamber **141**B in the manner described above such that high-k light element particles (e.g., deuterium ions D^+) directed from ion source **130**B impinge on frontside surface **111**B with sufficient energy to produce fusion reactions. As described above, some of the requisite light element gas molecules **145**B are sourced by low-k light element particles that detach from frontside surface **111**B. In cases where the supply of light element gas molecules **145**B generated in this manner is insufficient, neutron generation by apparatus **100**B may be beneficially enhanced by way of providing hydrogen source **150**B.

[0042] FIG. **5** shows an apparatus **100**C according to another exemplary embodiment in which a dual electrochemical cell setup is utilized both as a source of high-k light element particles and to supply low-k light element particles to a target electrode **110**C. A first electrochemical cell **120**C is configured and operates as described above to source low-k light element particles D to the frontside surface of a target electrode **110**C (e.g., by electrochemically driven deuterium transport through Pd), whereby fusion reactions are generated by collisions with high-k light element ions D^+ directed onto target electrode **110**C by plasma ion source **130**A. Vacuum chamber **141**C is also outfitted with a second electrochemical cell **160**C comprising a cathode **161**C, an electrolyte solution **162**C and an anode **163**C, where cathode **161**C is a thin Pd foil approximately 0.1 mm to 1 mm thick having a first (backside) surface in contact with electrolyte solution **162**C and a second (frontside) surface in contact with the contents of vacuum chamber **141**C. When cathode **161**C is subjected to a small negative DC bias (0 to 5 Volts), deuterium diffuses through the Pd foil and forms D_2 gas molecules into vacuum chamber **141**C in a manner similar to that described above. In one embodiment, a pump is connected to vacuum chamber **141**C through a valve (e.g., as described below with reference to FIG. **11**A), whereby the operating pressure of D_2 gas molecules **145**C in vacuum chamber **141**C can be controlled by throttling the valve to establish a dynamical vacuum in the chamber. With this arrangement, plasma ion source **130**A is supplied with D_2 from electrochemical cell **160**C. In one embodiment, plasma ion source **130**A comprises a hot filament that ionizes D_2 gas in vacuum chamber **141**C, and an ion accelerator configured to generate an electric field that accelerates and directs the D ions toward target electrode **110**C. Other plasma ion source types, including RF and microwave driven ion sources can also be embodied.

[0043] FIG. **6** shows a simplified apparatus **100**D in which electrochemical cell **120**D and plasma ion source (particle accelerator) **130**D are disposed in an over/under configuration. Apparatus **100**D includes a vacuum system **140**D having a primary vacuum chamber **141**D having an upper flange/opening **141**D-**1** and a lower flange/opening **141**D-**1**. Electrochemical cell **120**D, to which target electrode **110**D is operably coupled using details provided below, is operably configured (i.e., has a substantially cylindrical shape and size) for partial insertion into vacuum chamber **141**D through upper flange/opening **141**D-**1**. Similarly, plasma ion source **130**D is operably configured for partial inserting through lower flange/opening **141**D-**2** into vacuum chamber **141**D. As described below with reference to the specific embodiments shown in FIGS. **7** to **10**, this over/under configuration facilitates optimal positioning between target electrode **110**D and plasma ion source **130**D with minimal effort.

[0044] FIG. **7** shows an apparatus **100**E that represents a first embodiment of the over/under configuration described with reference to FIG. **6**. Apparatus **100**E is characterized by having a tube-shaped target electrode **110**E that forms a containment structure for electrochemical cell **120**E, and by having a plasma ion source **130**E including a cylindrical plasma electrode **131**E disposed around tube-shaped target electrode **110**E. More specifically, target electrode **110**E includes an electrically conductive light-element-absorbing material (e.g., Pd) that is machined or otherwise formed into a tube-shaped structure having a lower closed-end portion **113**E, an opened-end portion **114**E, and a cylindrical central portion **115**E extending between lower closed-end portion **113**E and opened-end portion **114**E. Target electrode **110**E is fixedly connected to an upper flange **141**E-**1** of a vacuum chamber **141**E such that a portion of cylindrical central portion **115**E including closed-end portion **113**E extends into vacuum chamber **141**E, and such that opened-end portion **114**E is disposed outside of vacuum chamber **141**E. Electrochemical cell **120**E includes an electrolyte solution **122**E that is contained within tube-shaped target electrode **110**E such that it contacts a cylindrical inside (backside) surface of cylindrical central portion **115**E, an electrochemical anode **124**E disposed in contact with electrolyte solution **122**E, and a bias source **126**E. During operation bias source **126**E is actuated to apply a bias voltage V_{bias} between

electrochemical anode **124**E and tube-shaped target electrode **110**E, thereby causing low-k light element particles (e.g., deuterium particles D) to migrate out of electrolyte solution **122**E through the cylindrical inside surface of cylindrical central portion **115**E and become disposed on a cylindrical outer surface of cylindrical central portion **115**E in a manner similar to that described above. Plasma ion source **130**E is fixedly connected to a lower portion of vacuum chamber **141**E such that cylindrical plasma electrode **131**E surrounds the cylindrical inside surface of cylindrical central portion **115**E. During operation, a suitable high voltage signal V_p is applied to generate a cylindrical plasma discharge region **133**E between cylindrical plasma electrode **131**E and tube-shaped target electrode **110**E, thereby directing high-k light element particles against the entire outer cylindrical surface of tube-shaped target electrode **110**E. Apparatus **100**E is therefore able to increase neutron generation for a given vacuum chamber size by providing a substantially larger fusion reaction area than can be achieved using the disk-shaped electrodes approaches described below.

[0045] FIG. **8** shows an apparatus **100**F representing a second over/under configuration characterized by having a disk-shaped target electrode **110**F that is fixedly attached to an electrochemical cell **120**F, and by having a plasma ion source **130**F including a disk-shaped counter electrode (vacuum anode) **131**F that is positioned to generate a disk-shaped plasma discharge region **133**F that directs high-k light element particles onto a downward-facing (frontside) surface of target electrode **110**F. Chemical cell **120**F includes a cylindrical housing **121**F comprising an inert, dielectric plastic and having a lower, closed-end portion **121**F-**1** and an opposing upper opened-end portion **121**F-**2**. Cylindrical housing **121**F is fixedly connected to an upper flange **141**F-**1** of a vacuum chamber **141**F such that lower-end portion **121**F-**1** is disposed inside vacuum chamber **141**F, and such that opened-end portion **121**F-**2** is disposed outside of vacuum chamber **141**F. In a specific embodiment cell **120**F includes an electrolyte solution **122**F comprising D_2O and D_2SO_4 (deuterated sulfuric acid), and target electrode **110**F includes an electrically conductive light-element-absorbing material (e.g., Pd foil having a thickness of 0.1 mm to 1 mm and a diameter of approximately one inch). Target electrode **110**F is fixedly attached over a lower (closed) end **121**F-**1** of cylindrical housing **121**F such that a vacuum-tight seal is formed between an interior of vacuum chamber **141**F and an interior of cylindrical housing **121**F. Electrolyte solution **122**F is contained within cylindrical housing **121**F such that it contacts an upper (backside) surface of target electrode **110**F. Plasma ion source **130**F is fixedly connected to a lower vacuum chamber flange **141**F-**2** and extends into vacuum chamber **141**F such that disk-shaped plasma electrode **131**F is maintained at a predetermined distance from target electrode **110**F. Both upper and lower vacuum flanges **141**F-**1** and **141**F-**2** are electrically isolated from the wall of vacuum chamber **141**F to facilitate subjecting target electrode **110**F to a pulsed negative bias −Vpp with respect to a positive pulsed bias Vpp applied to plasma electrode **131**F. This may be accomplished multiple ways, including grounding plasma electrode **131**F while sending a negative pulse to target electrode **110**F, or by grounding target electrode **110**F while sending a positive pulse to plasma electrode **131**F. In practical embodiments multiple plasma electrodes **131**F are utilized and configured based on a parallel-plate geometry for the anode and cathode, comprising ca 1" diameter disks for each electrode.

[0046] FIG. **9** depicts an electrochemical cell **120**G that may be utilized in place of cell **120**F in a practical implementation of apparatus **100**F (FIG. **7**). Cell **120**G includes a containment unit **121**G having a cylindrical containment housing **121**G-**1** and a clamping assembly **121**G-**2** disposed at its lower end, a target electrode **110**G that is secured by way of clamping assembly **121**G-**2** such that an electrolyte solution **122**G disposed in a container cavity **123**G contacts a backside surface of target electrode **110**G. In one embodiment cylindrical containment housing **121**G-**1** comprises an inert, dielectric plastic (e.g. PEEK) defining a cylindrical volume of approximately 20 ml and is open at its upper end. Clamping assembly **121**G-**2** includes a clamping flange **121**G-**21** that is integrally connected to cylindrical containment housing **121**G-**1**, and disk-shaped target electrode **110**G is held between one or more rubber (e.g. Viton) O-rings **121**G-**22** and one or more plastic clamping disks **1221**G-**23** that are in turn connected by dielectric screws **121**G-**24**. This configuration affords the mechanical support required for operation with a significant pressure differential across target electrode **110**G.

[0047] According to an aspect of the embodiment shown in FIG. **9**, cell **120**G includes both a counter electrode **124**G and a reference electrode **125**G that are disposed (i.e., operably supported) in container cavity **123**G such that both electrodes contact electrolyte solution **122**G. Counter electrode **124**G is configured to apply bias voltage V_{bias} to electrolyte solution **122**G, and functions in a manner described in the various embodiments presented above. Reference electrode **125**G functions to measure the cell's anode and cathode potentials with respect to a well-known reference potential V_{ref}. Because the varied electrochemical reactions that may occur at the electrodes are voltage dependent, the measurement of electrode potential with respect to a standard reference helps to define each electrode's operating regime. In one embodiment reference electrode **125**G has the same construction as counter electrode **124**G and is configured to apply reference voltage V_{ref} to electrolyte solution **122**G.

[0048] FIG. **10** depicts an electrochemical cell **120**H according to another exemplary embodiment. Cell **120**H is similar to cell **120**G (described above) in that it includes a containment unit **121**H having a cylindrical containment housing **121**H-**1** having a clamping assembly **121**H-**2** disposed at its lower end, and includes a target electrode **110**H that is secured by way of clamping assembly **121**H-**2** such that an electrolyte solution **122**H disposed in container cavity **123**H contacts a backside surface of target electrode **110**H, with an electrochemical anode **124**H operably disposed in container cavity **123**H such that it applies a bias voltage to electrolyte solution **122**H. The composition and/or structure of each of these elements is consistent with corresponding elements described in any of the embodiments set forth above.

[0049] Referring the upper portion of FIG. **10**, electrochemical cell **120**H differs from the previous embodiments in that containment unit **120**H further includes an upper containment structure **121**H-**3** that is configured to effectively seal the upper end of container cavity **123**H (i.e., upper containment structure **121**H-**3** makes container cavity **123**H essentially gas-tight, and therefore may include a pressure release mechanism **128**H for safety). According to

the present embodiment, upper containment structure **120**H-**3** ensures that light element particles sourced from electrolyte solution **122**H are not lost due to the evolution of gas at target electrode (electrochemical cathode) **110**H. The release of hydrogen isotope gas molecules (e.g., D_2 and/or T_2) at the interface between electrolyte solution **122**H and target electrode **110**H is commonly referred to as the hydrogen evolution reaction, or HER. In one embodiment, cell **120**H includes a recombiner **129**H that is configured to catalyze the recombination of hydrogen isotope gas from the HER process with oxygen, thereby generating heavy water that is then returned to electrolyte solution **122**H. In another embodiment, the level of bias voltage V_{bias} is maintained at a sufficiently low magnitude to avoid the production of significant gas by the HER process. In another embodiment, electrolyte solution **122**H includes one or more additives that function to suppress the HER process (e.g., water-in-salt electrolytes are designed to coordinate each water molecule with surrounding salt ions, thereby reducing each water molecule's availability to participate in the HER process at target electrode's surface).

[0050] Although the present invention is described above with specific reference to neutron generators, the present invention may also be beneficially utilized in a broader application as a tool for discovering and controlling new energy efficient ways to enhance nuclear reaction rates. Specifically, in addition to increased neutron generation, the enhanced fusion reaction rates achieved by way of combining electrochemistry and low energy ion sources also increases the production rate of other fusion reaction products, and the study of these other fusion reaction products may lead to a significantly greater understanding of both fusion and fission reactions. As such, by modifying the basic apparatus arrangements described above to include one or more reaction product detecting systems that are operably configured to detect and measure the fusion reaction products, beneficial aspects of the present invention may expanded from merely sourcing fusion reaction products to facilitating research that may lead to breakthroughs in the field of nuclear fusion science.

[0051] FIGS. **11**A, **11**B and **12** are simplified schematic diagrams showing a generalized fusion reaction product sourcing apparatus **100**J that is enhanced to facilitate nuclear fusion science research according to an exemplary embodiment. FIG. **11**A depicts apparatus **100**J from a side-view perspective, FIG. **11**B depicts apparatus **100**J from a top-view perspective, and FIG. **12** shows exemplary electrical sources and connections utilized by apparatus **100**J.

[0052] Referring to FIG. **11**A, similar to the embodiments described above, apparatus **100**J includes a target electrode **110**J disposed on an electrochemical cell **120**J inside a primary vacuum chamber **141**J of a vacuum system **140**J and operably positioned to receive high-k light element particles from a plasma ion source (particle accelerator) **130**J, where each of these structures is configured in accordance with details provided in the embodiments set forth above. Vacuum system **140**J includes a gas inflow antechamber **142**J-**1** and a gas outflow antechamber **142**J-**2** that are operably coupled to primary vacuum chamber **141**J to facilitate the optional introduction of light element gas molecules (e.g., D_2 and/or T_2) and to facilitate the optional isolation of fusion reaction product particles (e.g., He-3 atoms). Inflow antechamber **142**J-**1** is coupled to an external gas supply **150**J by way of a mass flow controller **152**J and a valve **154**J and is also coupled to a primary chamber vacuum gauge **143**J. Outflow antechamber **142**J-**2** is coupled to primary vacuum chamber **141**J by a flow reduction valve **144**J and is also coupled to a primary chamber vacuum pump **146**J by way of a variable flow valve **148**J. Referring to FIG. **12**, electrochemical cell **120**J receives bias voltage V_{bias} and optional reference voltage V_{ref} from an electrochemical power supply **300**, which also provides an associated ground signal (0V) to target electrode **110**J by way of a feedthrough **301**. A high voltage pulser **304** is controlled by a pulse signal generator **306** to generate plasma signal V_p as a high voltage pulse that is utilized by plasma ion source **130**J. The structural arrangements and electrical connections depicted in FIGS. **11**A, **11**B and **12** are not intended to be limiting.

[0053] Apparatus **100**J is further enhanced to facilitate nuclear fusion science research by way of including one or more reaction product detecting systems that are operably configured to detect fusion reaction products generated by the fusion reactions occurring on target electrode **110**J. For example, referring to FIG. **11**A, a sampling chamber **310** is operably coupled to outflow antechamber **142**J-**2** by way of a variable flow valve **312**. The vacuum atmosphere inside sampling chamber **310** is controlled by a sampling chamber vacuum pump and associated vacuum gauge **316** to facilitate capturing fusion reaction product particles that may be present in outflow antechamber **142**J-**2**. The particles captured by sampling chamber **310** may be detected and measured using one or more reaction product detecting system **320** (e.g., a residual gas analyzer and/or a mass spectrometer) that is/are operably coupled to sampling chamber **310**. Alternatively (or in addition), as indicated in FIG. **11**B, one or more reaction product detecting systems (e.g., a neutron detector **330**, a charged particle detector **340**, or a gamma ray detector (not shown)) may be operably positioned to detect associated reaction products generated inside primary vacuum chamber **141**J.

[0054] Although the present invention has been described with respect to certain specific embodiments, it will be clear to those skilled in the art that the inventive features of the present invention are applicable to other embodiments as well, all of which are intended to fall within the scope of the present invention.

1. An apparatus for sourcing fusion reaction products comprising:

a target electrode comprising a light-element-absorbing material;

an electrochemical cell including an electrolyte solution containing low-kinetic-energy (low-k) light element particles; and

a particle accelerator configured to direct a plurality of high-kinetic-energy (high-k) light element particles toward the target electrode,

wherein the electrochemical cell is configured to maintain contact between the electrolyte solution and the target electrode such that some of the low-k light element particles are absorbed from the electrolyte solution into the target electrode, and

wherein the particle accelerator is configured to provide each said high-k light element particle with sufficient energy to generate a fusion reaction when said each high-k light element particle operably collides with an associated said low-k light element particle absorbed by the target electrode.

2. The apparatus of claim 1,
wherein the target electrode has a first surface and an opposing second surface,
wherein the electrochemical cell is configured to maintain contact between the electrolyte solution and the second surface of the target electrode, and
wherein the particle accelerator is configured to direct at least a portion of the plurality of high-k light element particles toward the first surface of the target electrode.

3. The apparatus of claim 2, wherein the electrochemical cell further comprises an electrochemical anode disposed in contact with the electrolyte solution and operably coupled to a bias source that is configured to apply an electrochemical bias between the target electrode and the electrochemical anode such that the low-k light element particles are driven from the electrolyte solution to the second surface, whereby the driven low-k light element particles are absorbed through the second surface and diffuse through the light-element-absorbing material to the first surface.

4. The apparatus of claim 3, further comprising a bias control device operably coupled to the bias source and configured to adjust a level of the electrochemical bias applied to the electrochemical anode in response to an externally applied bias control signal, whereby a diffusion rate of the low-k light element particles through the light-element-absorbing material is selectively adjustable by way of variances in a level of the externally applied bias control signal.

5. The apparatus of claim 4, wherein the target electrode comprises a hydrogen absorbing material and both the low-k light element particles and the high-k light element particles comprise hydrogen isotope particles.

6. The apparatus of claim 5, wherein the target electrode comprises palladium and the electrolyte solution comprises hydrogen isotope particles.

7. The apparatus of claim 2, further comprising a vacuum chamber containing a rarefied atmosphere comprising light element gas molecules,
wherein the target electrode is configured such that the first surface is exposed to the rarefied atmosphere,
wherein the particle accelerator comprises a plasma ion source including a counter electrode disposed in the vacuum chamber and configured to produce a plasma discharge between the counter electrode and the target electrode such that the high-k light element particles comprise dissociated light element gas molecules that are accelerated by the plasma discharge toward the first surface of the target electrode.

8. The apparatus of claim 7, further comprising at least one of a hydrogen source and a second electrochemical cell operably configured to supply light element gas molecules into the vacuum chamber.

9. The apparatus of claim 7,
wherein the target electrode comprises a tube-shaped structure including a cylindrical central portion fixedly connected to an upper flange such that a first portion of the tube-shaped structure is disposed inside the vacuum chamber and a second portion of the tube-shaped structure is disposed outside of the vacuum chamber,
where the electrolyte solution is contained within target electrode such that the low-k light element particles diffuse through the cylindrical central portion of the tube-shaped target electrode, and
wherein the plasma ion source includes a cylindrical counter electrode that surrounds the cylindrical central portion of the tube-shaped target electrode.

10. The apparatus of claim 7,
where the electrochemical cell comprises a cylindrical housing containing the electrolyte solution, the electrochemical cell being mounted onto a first flange of the vacuum chamber such that a first end of the cylindrical housing is disposed inside the vacuum chamber,
wherein the target electrode comprises a disk-shaped structure fixedly connected to the first end of the cylindrical housing, and
wherein the plasma ion source includes one or more disk-shaped counter electrodes disposed in parallel with the disk-shaped target electrode.

11. The apparatus of claim 1, wherein the electrochemical cell includes both a counter electrode and a reference electrode disposed in contact with the electrolyte solution.

12. The apparatus of claim 1, wherein the electrochemical cell comprises a recombiner.

13. The apparatus of claim 1, further comprising at least one of a residual gas analyzer, a mass spectrometer, a neutron detector, a charged particle detector and a gamma ray detector operably configured to detect fusion reaction products generated by the fusion reactions.

14. A method for sourcing nuclear fusion products, the method comprising:
electrochemically loading a plurality of low low-kinetic-energy (low-k) light element particles into a target electrode such that some of said low-k element atoms are disposed on a first surface of the target electrode; and
directing a plurality of high-kinetic-energy (high-k) light element particles against the first surface, wherein each said high-k light element particle has sufficient energy to produce a fusion reaction when said each high-k light element particle operably collides with an associated said low-k light element particles disposed on the first surface.

15. The method of claim 14,
wherein the target electrode comprises an electrically conductive light-element-absorbing material having a second surface that opposite to the first surface, and
wherein the electrochemically loading further comprises:
maintaining an electrolyte solution in contact with the second surface of the target electrode, the electrolyte solution including the low-k light element particles, and
applying one of a bias voltage and a bias current to the electrolyte solution such that some of the low-k light element particles disposed in the electrolyte solution are driven to the second surface of the target electrode, and then diffuse through the target electrode to the first surface.

16. The method of claim 14, wherein the electrochemically loading further comprises controlling a diffusion rate of the low-k light element particles through the target electrode to the first surface by way of controllably adjusting a level of said one of the bias voltage and the bias current.

17. The method of claim 14, wherein the electrochemically loading comprises loading hydrogen isotope particles into said target electrode, wherein said target electrode comprises palladium.

18. The method of claim **14**, wherein said directing the plurality of high-k light element particles is performed in a rarified environment comprising light element gas molecules, and further comprises utilizing a plasma discharge such that the high-k light element particles comprise dissociated light element gas molecules that are accelerated by the plasma discharge toward the first surface of the target electrode.

19. The method of claim **18**, wherein the light element gas molecules are entirely supplied by detachment of the low-k element atoms from the first surface of the target electrode.

20. The method of claim **18**, wherein the light element gas molecules are at least partially supplied from one of a hydrogen source and a second electrochemical cell that are operably configured to supply light element gas molecules into the vacuum chamber.

21. The method of claim **15**,

wherein said electrochemically loading comprises disposing said electrolyte solution in a tube-shaped target electrode having a cylindrical outer surface, and

wherein said directing comprises disposing a cylindrical counter electrode around the cylindrical outer surface of the tube-shaped target electrode and driving the cylindrical counter electrode such that a plasma cylindrical plasma discharge is generated between the cylindrical counter electrode the cylindrical outer surface of the tube-shaped target electrode.

22. The method of claim **15**,

wherein said electrochemically loading comprises disposing said electrolyte solution in a cylindrical housing containing the electrolyte solution such that the electrolyte solution contacts a disk-shaped target electrode secured to a first end of the cylindrical housing, and

wherein said directing comprises disposing a disk-shaped counter electrode adjacent to the disk-shaped target electrode and driving the disk-shaped counter electrode such that a plasma cylindrical plasma discharge is generated between the disk-shaped counter electrode the disk-shaped target electrode.

23. The method of claim **15**, wherein said electrochemically loading further comprises utilizing a recombiner to catalyze a recombination of light element gas molecules with oxygen.

24. The method of claim **14**, further comprising utilizing at least one of a residual gas analyzer, a mass spectrometer, a neutron detector, a charged particle detector and a gamma ray detector to detect fusion reaction products generated by the fusion reactions.

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