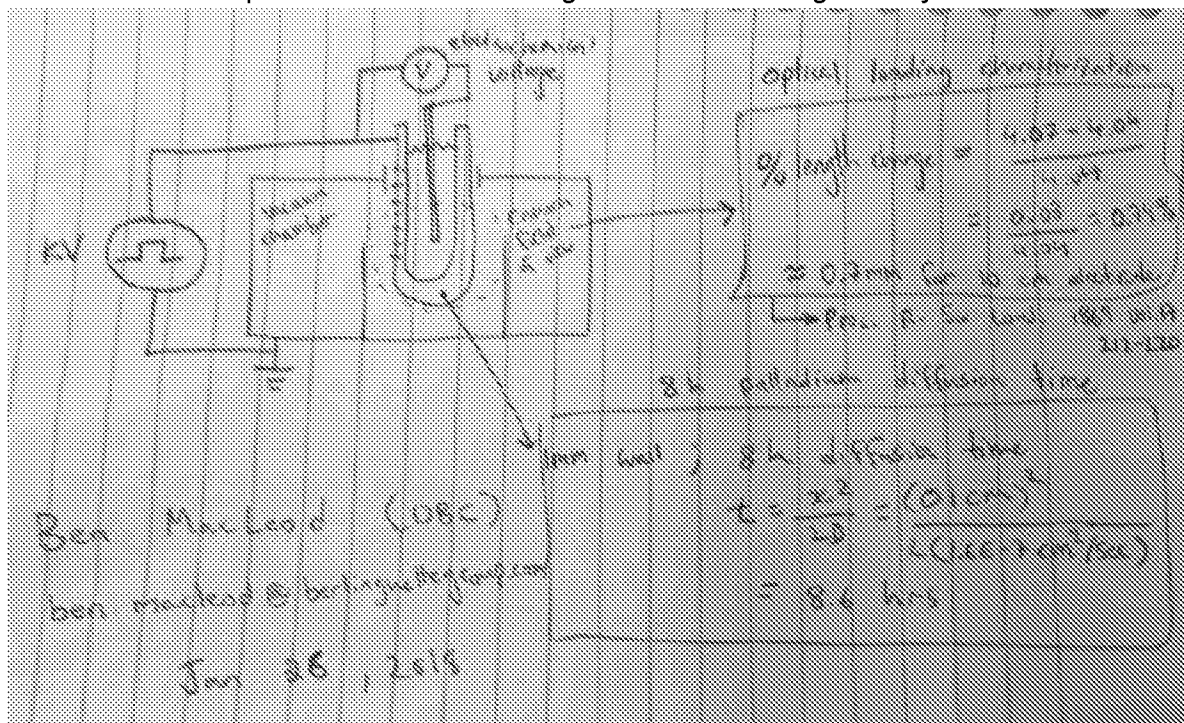


APPENDIX A

Conceptual reduction to practice

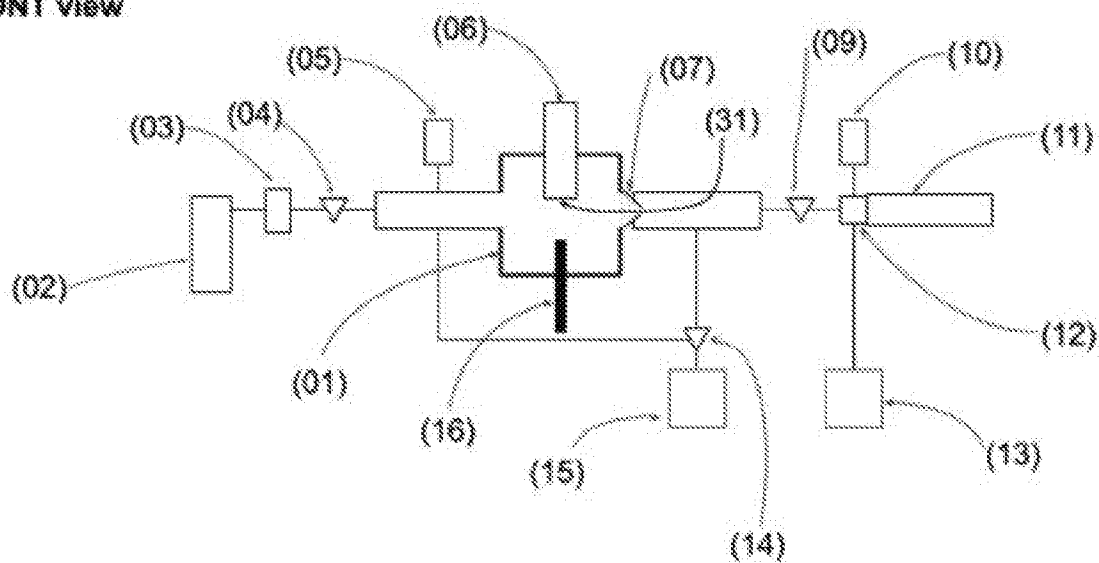
Below is a sketch by Ben MacLeod following discussions at the Charleston Peer group meeting on integration of hydrogen loading techniques with plasmas and beams, Jan 26, 2018. The "Ross tube" concept shown was later changed to a flat Pd foil geometry.



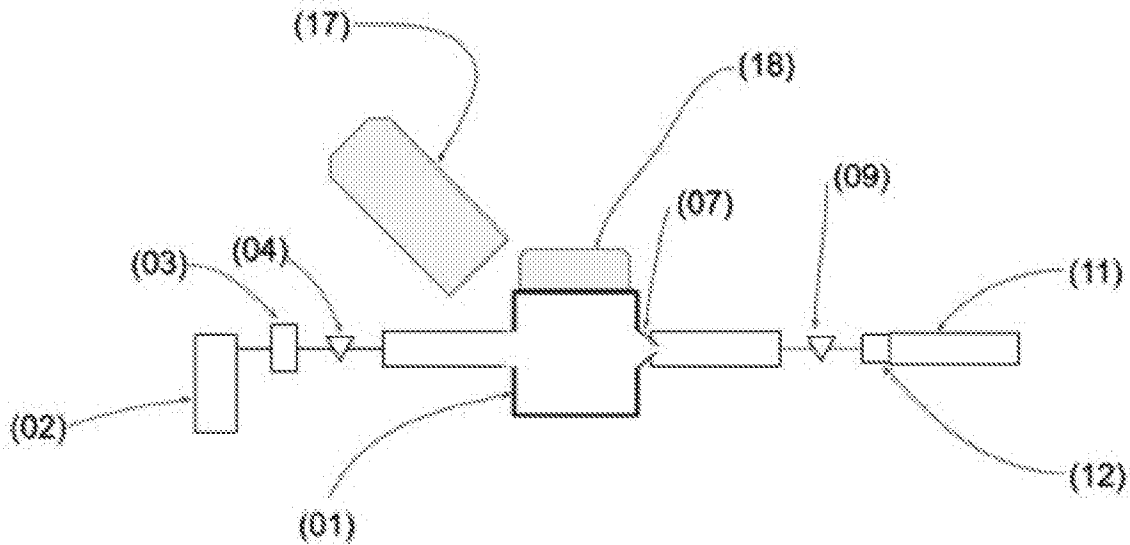
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Below are line drawings and associated descriptions showing the apparatus.

FRONT view

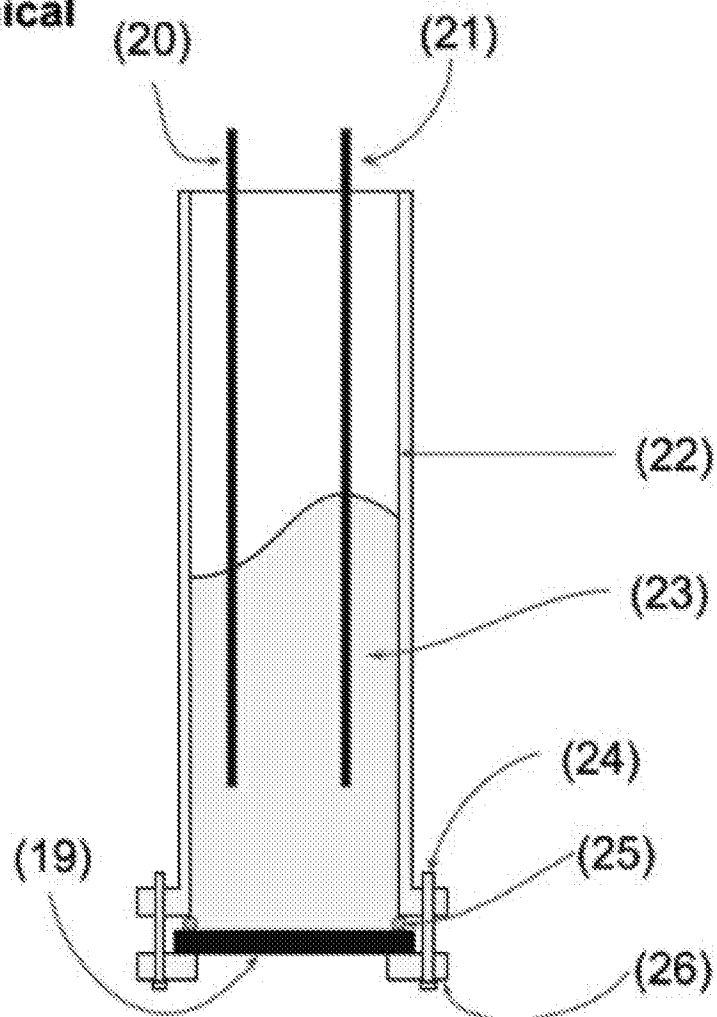


TOP view

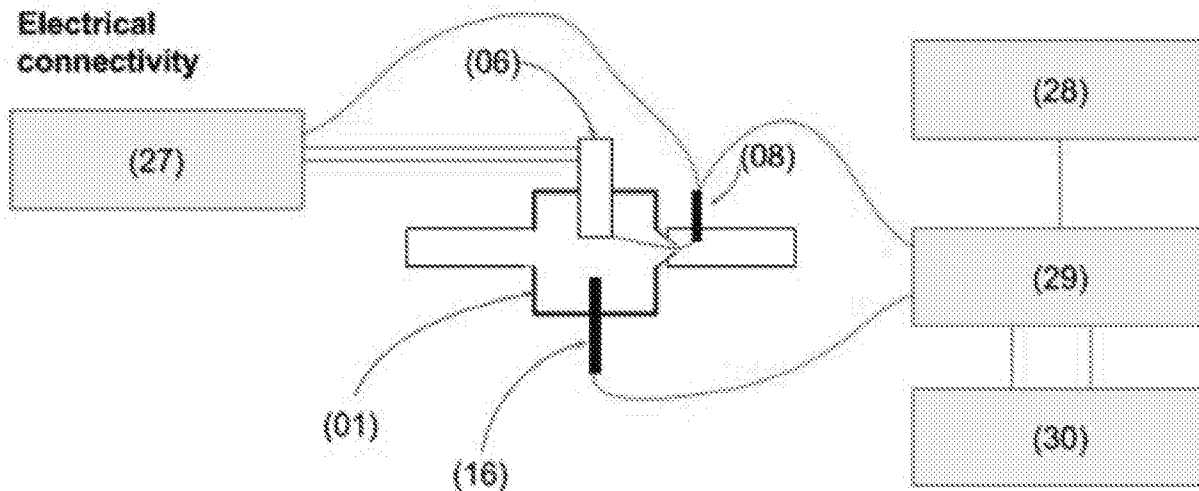


APPENDIX A

**Electrochemical
cell**



**Electrical
connectivity**



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ID	Description
01	Primary vacuum chamber
02	External gas supply
03	Mass flow controller
04	Valve
05	Vacuum gauge (primary chamber)
06	Electrochemical cell
07	Flow reduction valve
08	High voltage electrode feedthrough (plasma electrode and electrochemical working electrode)
09	Variable flow valve
10	Vacuum gauge (sampling chamber)
11	Residual gas analyzer / mass spectrometer
12	Sampling chamber
13	Vacuum pump (sampling chamber)
14	Variable flow valve
15	Vacuum pump (primary chamber)
16	Vacuum anode
17	Neutron detector
18	Charged particle detector
19	Plasma target (vacuum facing surface of hydrogen permeable cathode)
20	Electrochemical reference electrode
21	Electrochemical counter electrode (anode)
22	Electrochemical cell
23	Electrolyte solution
24	Screws for fastening
25	O-rings for fastening

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26	Clamping assembly
27	Electrochemical power supply (potentiostat-galvanostat)
28	Pulse signal generator
29	High voltage pulser
30	High voltage power supply
31	Hydrogen permeable cathode

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 D_2O , 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 ~ 1 nm) the second cathode surface serves as a target for bombardment with energetic light elements to produce fusion reactions.

In the embodiment illustrated above, a flux of hydrogen released from the second cathode surface and entering the vacuum chamber then feeds a plasma discharge that is used to accelerate hydrogen ions back into the second cathode surface. In this embodiment, the plasma discharge occurs between the second cathode surface and a vacuum anode situated in the vacuum chamber. A pulsed plasma discharge negatively biases the cathode with respect to the vacuum anode.

An aspect of this invention is that the target's hydrogen concentration can be controlled by adjusting the level of the electrochemical potential bias applied between the electrochemical anode and the cathode.

It is a further aspect of this invention to ensure that hydrogen sourced from the electrolyte is not lost due to the evolution of hydrogen gas at the electrochemical cathode. The release of hydrogen at the interface between the electrolyte and the electrochemical cathode is commonly referred to as the hydrogen evolution reaction, or HER. In one embodiment, the apparatus contains a recombiner, the purpose of which is to catalyze the recombination of hydrogen from the HER with oxygen to resupply the resulting water to the electrolyte.

In another embodiment, the electrochemical cell potential is maintained at a sufficiently low magnitude to avoid the HER.

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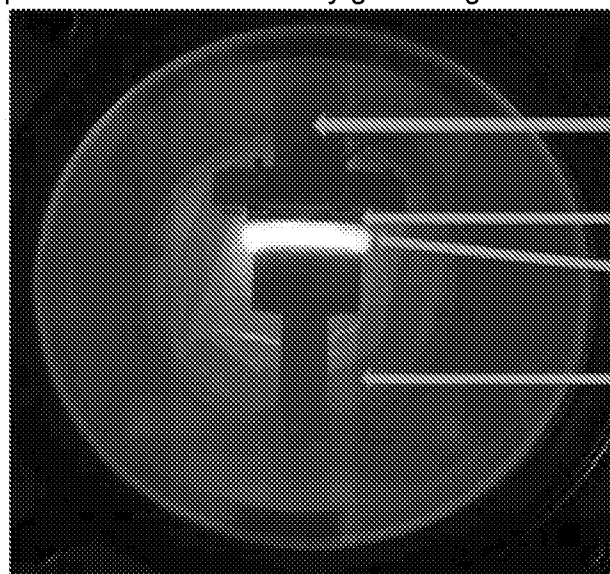
In another embodiment, additives are used in the electrolyte to suppress the HER. One example of this embodiment is the use of water-in-salt electrolytes, which are designed to coordinate each water molecule with surrounding salt ions thereby reducing each water molecule's availability to participate in the HER at the cathode surface.

Physical reduction to practice

Below is a photo taken at the Lawrence Berkeley Lab, building room B58. The photo shows a bright violet colored deuterium plasma discharge taken through the viewport of a vacuum chamber. Above the discharge is a Pd foil (0.1 to 1 mm thick), connected to an electrochemical cell constructed within an upper vacuum chamber flange. Within the upper vacuum chamber flange is an electrolyte comprising D_2O and D_2SO_4 (deuterated sulfuric acid). The electrolyte is in contact with the upper surface of the Pd foil. The lower surface of the Pd foil forms an inner surface within the vacuum chamber. A vacuum tight seal separates the upper and lower surfaces of the Pd foil.

Below the bright violet colored deuterium plasma discharge is a lower vacuum chamber flange through which is fed a vacuum anode which is held in proximity to the cathode.

The upper and lower vacuum flanges are electrically isolated from the chamber so that the cathode may be subjected to a pulsed negative bias with respect to the anode. This may be accomplished multiple ways, including either by grounding the anode and sending a negative pulse to the cathode or by grounding the cathode and sending a positive pulse to the anode.



- electro-chemical cell containing D_2O and D_2SO_4 , run with low voltage, low current power supply, operated at negative HV or at ground potential
- Pd foil (~0.1 to 1 mm thick)
- deuterium plasma discharge, ~1 to 100 mA, 0.1 to a few kV, pulsed, ~20 micro s, ~50 Hz
- counter-electrode connected to HV feed through, at ground or at positive high voltage

vacuum chamber (6" cube)
D2 pressure: 0.1 to 1 few Torr

Operation of this apparatus was done in collaboration with the University of British Columbia (Curtis Berlinguette and Phil Schauer) with Phil present on site to run the electrochemical cell in coordination with plasma/ion and nuclear electronics operation. The design is based on discussions between Phil Schauer, Thomas Schenkel and Ben Macleod during the Summer 2018.

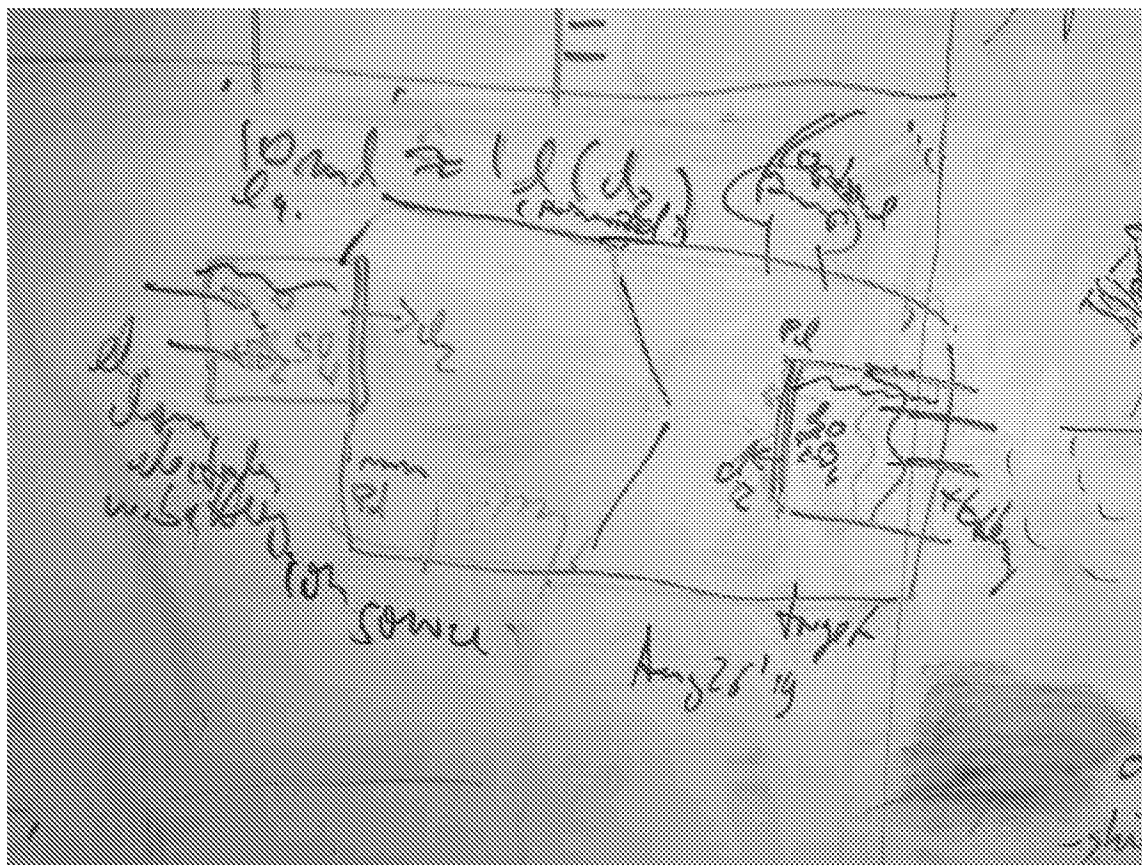
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Design details of the physical reduction to practice

The plasma electrodes are based on a parallel-plate geometry for the anode and cathode, comprising ca 1" diameter disks for each. In one embodiment the electrochemical cell comprises a cylindrical volume of approximately 20 ml of inert, dielectric plastic (e.g. PEEK) that is open on one end and terminated with an assembly to hold the electrochemical cathode on the other. One iteration of the cell design supports the electrochemical cathode by clamping of the cathode disk with rubber O-rings (e.g. Viton) between larger plastic disks that are in turn connected by dielectric screws. Such a design affords the mechanical support required for operation with a significant pressure differential across the electrode. Iterative development of the cell assembly will focus on improving the electric field geometry about the electrode to enable a wider range of applied plasma discharge voltages.

Dual electrochemical cell embodiment

Below is a white board photo taken Aug 26, 2019 showing a schematic of a dual electrochemical cell setup integrating an ion source and a target, where D_2 is provided for both the ion source and for the target by electrochemically driven deuterium transport through Pd.



In this embodiment a vacuum chamber is outfitted with a first electrochemical cell (left) comprising an anode, electrolyte and cathode. The cathode is a thin foil approximately 0.1 mm to 1 mm thick having a first surface in contact with the electrolyte and a second surface in

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contact with the contents of the vacuum chamber. When the cathode is subjected to a small negative DC bias (0 to 5 Volts) hydrogen is introduced into the Pd foil and diffuses through the foil into the vacuum chamber.

A pump, upper right, is connected to the vacuum chamber through a valve (not shown). The operating pressure of the hydrogen in the vacuum chamber can be controlled by throttling the valve to establish a dynamical vacuum in the chamber.

An ion source which is supplied by hydrogen from the first electrochemical cell comprises a hot filament (lower left) which ionizes hydrogen gas in the chamber. The ion source further comprises an ion accelerator illustrated by an electrically biased aperture (middle of drawing).

The apparatus further comprises an electrochemically loaded fusion target (middle right) consisting of elements that have been described previously.

Further insight into the nanoscale mechanisms of this invention

A previously unrecognized feature that led to this invention is the similarity of two critical length scales underlying the physical process that takes place on the cathode surface where ion beam fusion occurs. The two length scales we refer to are:

1. The implantation depth of the energetic ions that impinge on the cathode surface from the vacuum side. This depth is on the order of 1 nm for energetic ions with kinetic energy on the order of 1 kV (Czerski).
2. The thickness of the surface and sub-surface layer of strongly bound hydrogen on the palladium metal surface (Huang 2006). This depth is on the order of several atomic layers, which is coincidentally on same order (1 nm) as the implantation depth of the impinging energetic ions mentioned above.

The inventors recognized that the tendency for hydrogen to absorb preferentially at the surface of palladium (and other metals) could be exploited in this invention to create a hydrogen rich target surface.

Prooclaims

Structure

1. An apparatus for nuclear fusion comprising:
 - a light element absorbing electrode;
 - a light element containing electrolyte;
 - a source of energetic light elements;
 - wherein the energetic light elements are directed at the light element absorbing electrode and wherein light elements from the electrolyte are absorbed into the electrode.

Dependent structure claims

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- the light element absorbing electrode has a first surface and a second surface; the light element containing electrolyte is in contact with the first surface; the energetic light elements are directed at the second surface.
- apparatus including a second electrochemical electrode, wherein a voltage bias is applied to drive light elements into the light element absorbing electrode.
 - the second electrochemical electrode is an anode and the light element absorbing electrode is a hydrogen absorbing cathode
 - the light element absorbing electrode is substantially palladium
 - the second electrochemical electrode is a lithium absorbing electrode
 - the second electrochemical electrode is a silicon anode
 - the electrochemical electrode is a complex oxide cathode
- apparatus wherein energetic light elements are directed at the light element absorbing electrode using a plasma discharge
 - apparatus further comprising a rarefied gas of light elements, the plasma discharge occurring between the light element absorbing electrode and a counter electrode in the rarefied gas
 - apparatus in which the rarefied gas is supplied by light elements desorbing from the light element absorbing electrode
 - apparatus in which the plasma discharge is a glow discharge
 - apparatus in which the plasma discharge is electrically pulsed
- apparatus wherein the light element containing electrolyte contains an isotope of hydrogen
- apparatus wherein the light element containing electrolyte contains an isotope of lithium
- apparatus further comprising a second electrochemical cell supplying light elements to an energetic ion source.

Method

1. A method for fusing light elements comprising:
 - electrochemically absorbing a first supply of light elements into an electrode
 - impinging a second supply of light elements onto a surface of said electrode

Dependent claims

Variations suggested above within the structure claims

2. A method to control the amount of loading of the light element in the electrode, for use in achieving a desired loading range / light element flux at the target surface
 - where the e-chem is used to control the loading,
 - by means of electrical potential
 - by means of electrical current
 - by a combination of the above

APPENDIX A

Reference to prior art relating to water in salt electrolytes

This is an abstract from the Spring Materials Research Society meeting held in Phoenix, AZ in April of 2019. 10:45 AM QN06.05.02

Superconductive Rhenium Thin Films Electrodeposited from Water-in-Salt Electrolytes Qiang Huang², Yang Hu², William Sides², David Pappas¹ and Tyler

Lyons²; ¹National Institute of Standards and Technology, Boulder, Colorado, United States; ²Chemical and Biological Engineering, The University of Alabama, Tuscaloosa, Alabama, United States.

Electrodeposition has been used widely in the fabrication of microdevice and circuits because of the low cost, fast deposition rate, and, more importantly, the ease of scale-up. Electrodeposited superconductive films are of interest for cryogenic quantum devices as it avoids thermal perturbation resulted from the electrical heat. Such films are particularly of interest if the critical temperature (T_c) is above 4.2 K, which can be easily achieved with liquid helium. Recently, electrodeposited rhenium was demonstrated to show a critical temperature of about 6 K, representing a significant increase from its intrinsic 1.7 K[1]. However, electrodeposition of rhenium requires an acidic electrolyte, where significant hydrogen evolution is inevitable and causes inclusion of hydrogen and highly stressed or even cracked films.

On the other hand, a so-called hydration layer forms during the dissolution of salts in water. Such hydration process requires and “consumes” water molecules. When an electrolyte contains a superhigh concentration of supporting salts, for example, alkali metal salts, the hydration of such salts can deplete the free water molecules in the aqueous electrolyte and significantly mitigates the evolution of hydrogen[2,3]. This paper presents a new electrodeposition method to synthesize superconductive rhenium films using water-in-LiCl electrolyte.

A limiting current density emerged upon the addition of 5 M LiCl into an acidic Re electrolyte. This lowered hydrogen evolution reaction not only limited the voltage drop due to the high current and solution resistance, but also enabled electrochemical studies at more negative potentials. An improved film morphology was observed with a suppressed hydrogen evolution currents when the water-in-salt electrolyte was used. A critical temperature of 6 K for as-deposited rhenium film was achieved and a decrease of T_c was observed for the films upon annealing at beyond 150 C. The details of chemical uniformity, grain structures, and T_c of such Re films will be presented. In addition, attempts to electrodeposit Re alloys with this water-in-LiCl electrolyte will be discussed as well.

REFERENCES

1. D.P. Pappas, D.E. David, R.E. Lake, M. Bal, R.B. Goldfarb, D.A. Hite, E. Kim, H.-S. Ku, J.L. Long, C.R.H. McRae, L.D. Pappas, A. Roshko, J.G. Wen, B.L.T. Plourde, I. Arslan, and X. Wu, Enhanced superconducting transition temperature in electroplated rhenium, *Applied Physics Letters*, 2018, 112(18), 182601.
2. L. Suo, O. Borodin, T. Gao, M. Olguin, J. Ho, X. Fan, C. Luo, C. Wang, and K. Xu, “Water-in-salt” electrolyte enables high-voltage aqueous lithium-ion chemistries, *Science*, 2015, 350(6263), 938.
3. L. Coustan, G. Shul, and D. Bélanger, Electrochemical behavior of platinum, gold and glassy carbon electrodes in water-in-salt electrolyte, *Electrochemistry Communications*, 2017, 77, 89.

APPENDIX B

**Can we discover and control new energy efficient ways to
enhance nuclear reaction rates ?**

Ideas for a TINA pilot in ARPA-E on new ways to control and enhance
nuclear reaction rates at low reaction energies

Thomas Schenkel, Lawrence Berkeley National Laboratory

Nov. 15, 2019

Can we discover and control new energy efficient ways to enhance nuclear reactions ?

Fusion

- Rates of fusion reactions are set 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 plasmas that are difficult and expensive
- We have observed that fusion reactions at a few keV can be enhanced 100-fold when the reactions take place in metals compared to the gas phase [1, 2]
- Preliminary results show large changes of the branching ratio in D-D fusion in experiments that combine electrochemistry and low energy ion beams indicating new nuclear processes (if confirmed)
- If we can understand the underlying mechanisms of these enhancements then this could lead to fusion energy without the need for very hot plasmas (without fulfilling the Lawson criteria), and a path to low cost, carbon free electricity
- The risk is that the observed effects can not be controlled well enough to be energy efficient

[1] T. Schenkel, et al., [arXiv:1905.03400](https://arxiv.org/abs/1905.03400) (J. Appl. Phys., in press)

[2] C. P. Berlinguette, et al., Nature 570, 45 (2019)

Can we discover and control new energy efficient ways to enhance nuclear reactions ?

Nuclear decay

- Nuclear reactions like alpha decay are determined by the internal structure of nuclei (as well as by the energy of reacting nuclei)
- Some reports show enhanced alpha decay of heavy elements in the presence of high electric fields from plasmons [3]
- If we can understand the underlying mechanisms then this could lead to much shorter half lives for the decay of radioactive nuclei with a path to nuclear energy harvesting and a much reduced burden due to radioactive waste
- The risk is that these early reports are faulty and that the electrical fields needed require big lasers that make the process too expensive

[3] A. V. Simakin, G. A. Shafeev, Quantum Electronics 41, 614 (2011), and several other by these authors

Can we discover and control new energy efficient ways to enhance nuclear reactions ?

- **Ideas for experiments:**

- Drive the loading of deuterium into metals by electrochemistry, and use low energy deuterium ions to trigger fusion reactions in the highly loaded metals (e. g. palladium)
- Detect neutrons, tritium, protons, helium and quantify fusion yields and branching ratios, $B = Y(p+T)/Y(n+^3\text{He})$
- A handful of data points to date indicate enhanced tritium production, and a strong change in the branching ratio of the D-D fusion reaction in the combined electro-chemistry and low energy ion experiments (preliminary, in progress, ...)
- Can we correlate the metal hydride lattice structure with D-D fusion yield enhancements ? E. g. using in situ electron diffraction while fusion reactions are induced by electro-chemistry and low energy ions in a series of materials
- Can we act on nuclear reaction rates and tunnel barriers with electrical fields from plasmons?
- Can we drive plasmon resonances with lasers and nanoparticles, then look for changes of fusion [4] and nuclear decay rates (alpha decay, electron capture type decay, analog to Be-7 decay changes at ~1% levels in oxides vs. metals, but then enhanced) [3]
- Ion beams (at low kinetic energy) are very energy inefficient in driving fusion reactions (because of collisional losses) but they can be used to enter a regime where some fusion can be observed. This can help open a learning path in materials design to enhance fusion reaction rates at lower and lower energies, towards a fraction of 1 eV and with efficient drivers (laser-plasmons, very low energy ions or plasmas) [1, 2]

[4] D. K. Fork, et al., US-10264661-B2 (2019)

Can we discover and control new energy efficient ways to enhance nuclear reactions ?

- Both fusion and nuclear decay enhancement studies require advances in theory, simulations/modeling and experiments
- The common factoring of nuclear reaction cross sections as the product of a geometric factor, the so called S-factor (which is supposed to contain all the nuclear physics) and the electron screening factor works very well for high reaction energies (and temperatures >100 million degrees) but might break down at energies below a few keV (and temperatures below a few million degrees), opening an opportunity to consider the full atomic-nuclear wave-function in the analysis of nuclear reactions in solid state environments.

$$\sigma_f(E, U_e) = \frac{1}{\sqrt{E(E+U_e)}} e^{-\sqrt{E_e/(E+U_e)}} S(E)$$

Cross section = geometric factor

* electron screening (atomic physics)

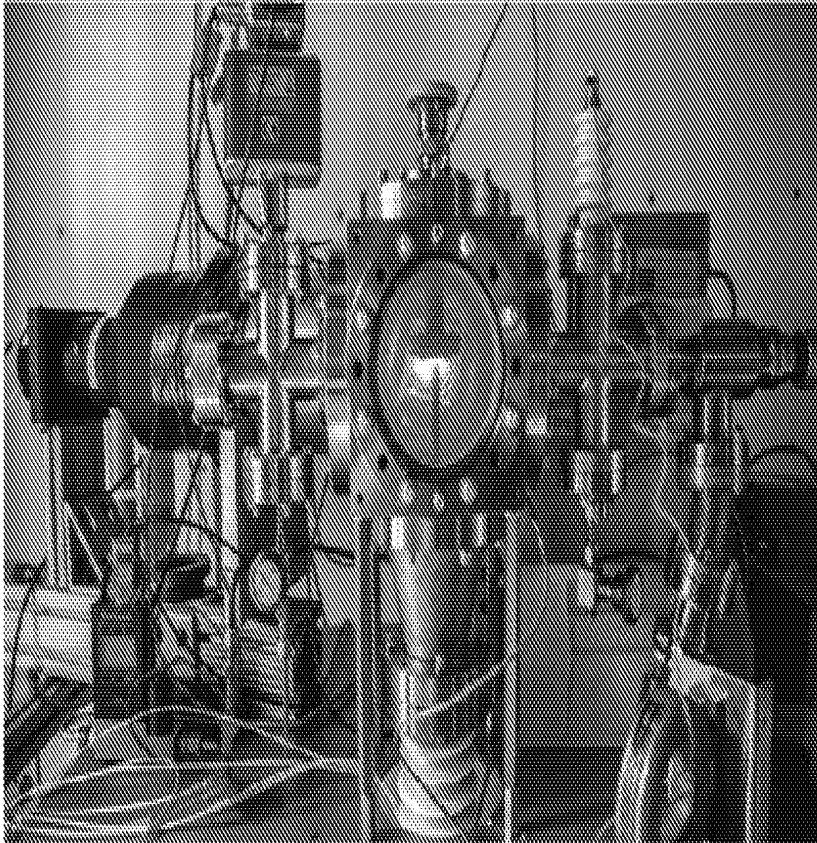
* astrophysical S-factor (nuclear physics)

(The cross section is a measure of the likelihood for of a nuclear reaction to take place, e. g. the likelihood for a fusion process in the collision for two hydrogen atoms).

Can we discover and control new energy efficient ways to enhance nuclear reactions ?

- In a TINA program a series of well defined hypothesis could be tested over the course of ~2 years to determine the scientific validity and depth as well as the technology promise of these directions
- Rough cost estimate: 4 to 5 projects at \$ 0.5 to 1 M/y for ~2 years, ~ \$ 4 to 10 M total
- Chances are that a TINA program in this area will lead to basic science discoveries and high impact publications, and it is quite possible that the observed effects then simply don't scale to anywhere near energy efficiency during follow up projects.
- It is also possible that a TINA program will open the door for a new learning path to control nuclear reactions and fusion processes much more efficiently then is possible today with disruptive impact on energy technology.

Can we discover and control new energy efficient ways to enhance nuclear reactions ?



Example of an experimental setup for low energy fusion studies sat Berkeley Lab (photo Berkeley Lab; P. Ball, MRS Bulletin, 44, 834, (2019))

- Ongoing collaboration of LBNL and UBC, funded by GOOGLE
- An electro-chemical solution is combined with palladium to load it with deuterium
- The Pd foil is then bombarded with ions from a plasma discharge
- We collect tritium and see activity consistent with 10 million tritium atoms in the solution
- But the normal D-D cross section at the ion energy of 0.4 keV is <1 pico barn, so we would expect only a few thousand fusion reactions and tritium atoms
- Neutron counts observed above background in 12 h run: none
- Systematics and control experiments in progress
- **If confirmed it opens the door for optimization of novel nuclear processes at low energies**

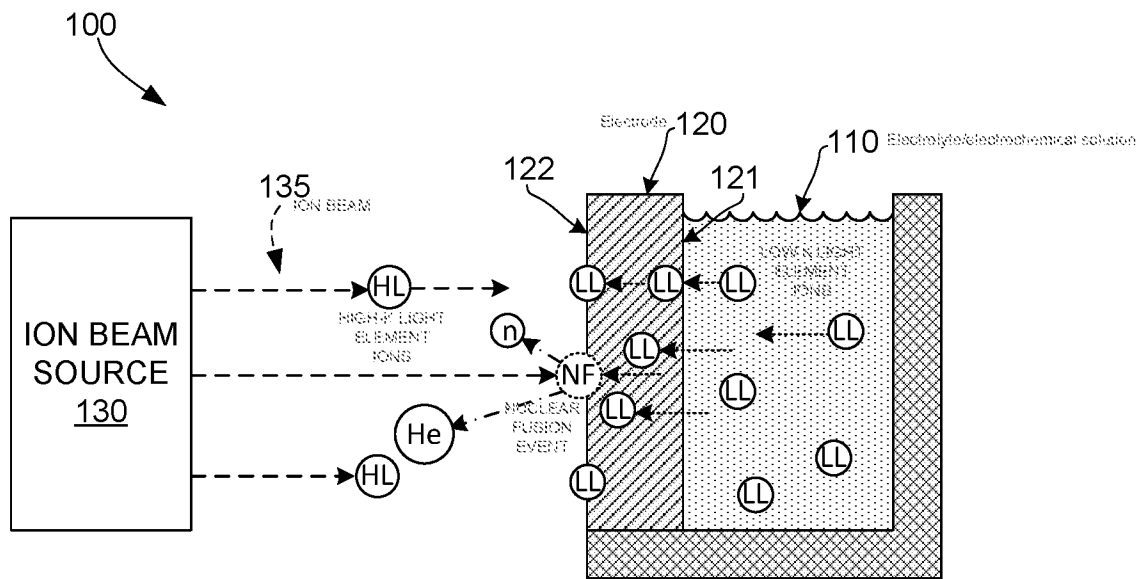


FIG. 1

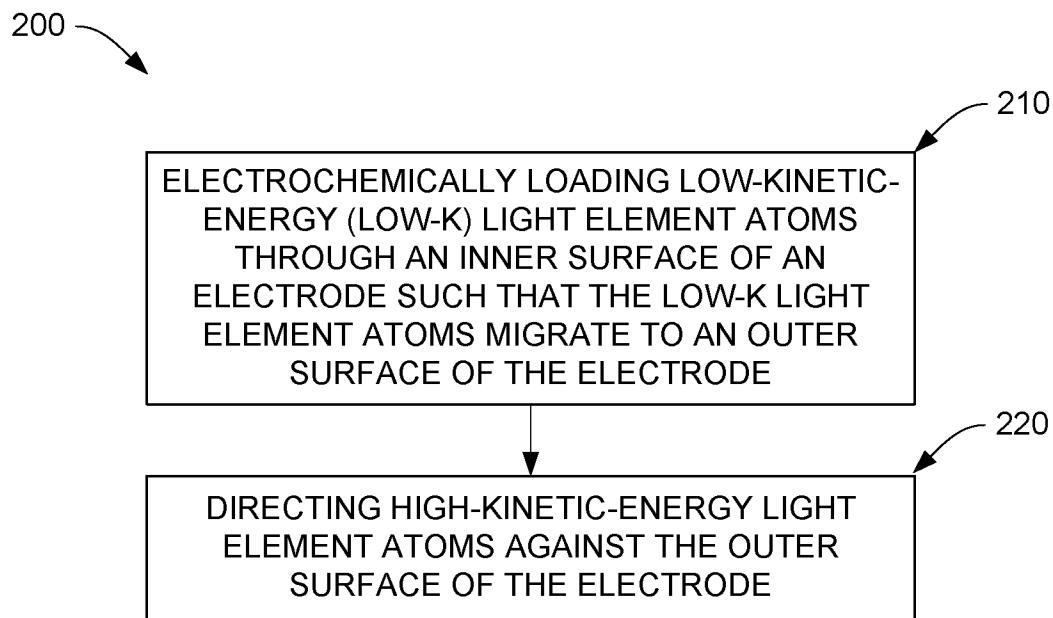


FIG. 2