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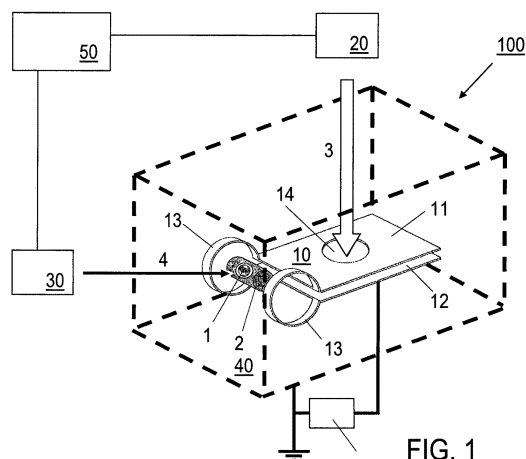
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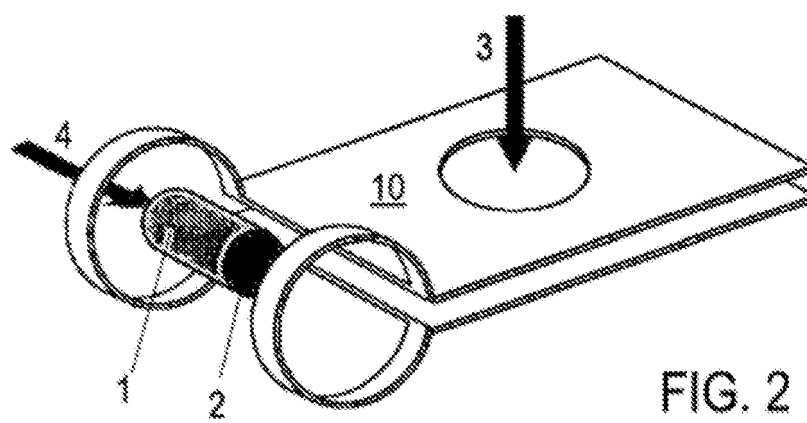
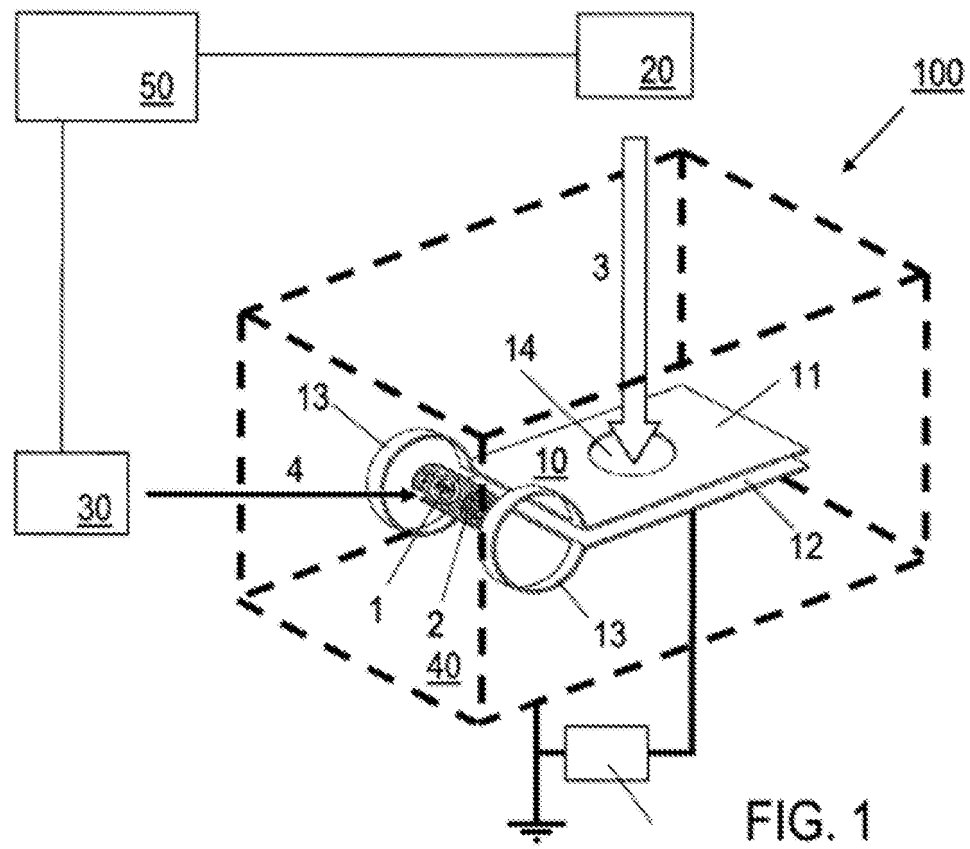
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(54) Title of the Invention: **Method for generating electrical energy by laser-based nuclear fusion and laser fusion reactor**  
Abstract Title: **Method for generating electrical energy by laser-based nuclear fusion and laser fusion reactor**

(57) A method for generating electrical energy comprises the steps of providing a fusion fuel (1), wherein the fusion fuel (1) is held in a magnetic field in a cylindrical reaction space (2), initiating nuclear fusion in the fusion fuel (1), wherein a fusion flame is produced by fusion laser pulses (4) with a pulse duration of less than 10 ps and a power of more than 1 petawatt, and converting the energy released during the nuclear fusion from the nuclei produced into power plant power, wherein the magnetic field has a field strength which is greater than or equal to 1 kilotesla, and the nuclear fusion has an energy efficiency of more than 500 per laser energy initiating the fusion flame of the fusion laser pulses (4). A nuclear fusion reactor which is configured for generating electrical energy is also described.





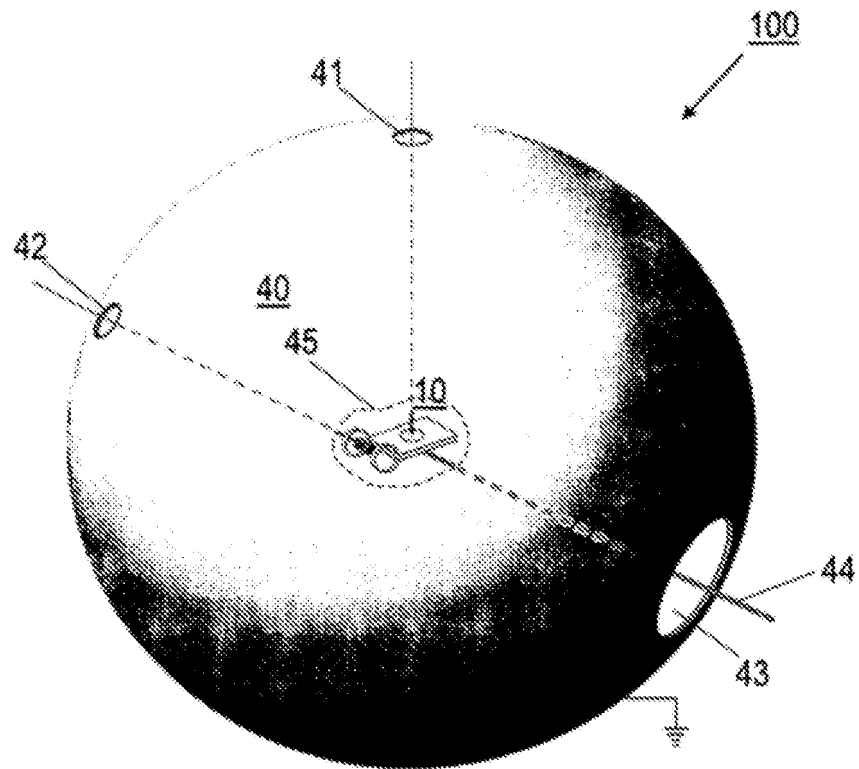


FIG. 3

METHOD FOR GENERATING ELECTRICAL ENERGY BY LASER-BASED  
NUCLEAR FUSION, AND LASER FUSION REACTOR

5     The invention relates to a method for generating electrical energy, which is based on  
the fusion of protons with the boron isotope 11 using laser radiation and magnetic fields  
and converting the energy that is released during the fusion into electrical energy. The  
invention also relates to a laser fusion reactor, which is configured for generating  
electrical energy by means of the laser-based fusion of protons with the boron isotope  
10    11. Uses for the invention are provided in the field of electric power generation.

Prior Art

In the description of the prior art, reference is made to the following publications:

15

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15 The most frequently used method of producing energy involves the burning of fossil fuels that contain carbon. For more than 200 years, the burning of fossil fuels has formed the basis for technological progress and economic prosperity. As a disadvantage, however, this process releases the combustion product carbon dioxide into the atmosphere, which can lead to undesirable changes in global climate.

20

Another method for producing energy is based on nuclear fission, in which the nuclear energy that is released is converted first into heat and then into electrical energy. Although the operation of nuclear power plants is economical, it has the disadvantage

that the disposal of radioactive waste is costly and risky. Furthermore, it involves the operational risk that a power plant accident can result in extreme, catastrophic damage.

Nuclear energy can also be released by nuclear fusion, in which lighter atomic nuclei  
5 are fused to form heavier atomic nuclei, releasing the energy  $E = mc^2$  ( $m$ : nuclear mass defect  $m$ ,  $c$ : speed of light) in the extremely high range of approximately 10 MeV per fusion reaction. However, with the exception of natural processes occurring in stars, nuclear fusion has heretofore been realized only in an uncontrolled manner in the form of exploding a fusion bomb. Controllable fusion power plants have been in  
10 development for decades, however despite major research efforts, they have not yet been successfully implemented in practice.

A fusion reaction which has been comprehensively studied is based on the fusion of the heavy hydrogen deuterium (D) with the super heavy hydrogen tritium (T) (D-T fusion).  
15 However, this fusion reaction is characterized by the undesirable production of radioactive radiation which results from the conversion, with neutrons, of initially non-radiative nuclei of harmless, non-radioactive materials into radioactive isotopes, e.g. within a reactor vessel.

20 All known methods for the controlled generation of nuclear fusion energy have a yield of less than 500 (energy produced per laser energy expended) with one exception. Nuckolls and Wood proposed in 2002 [13] that, as with the "fast ignition" scheme, a nanosecond-long laser pulse will produce approximately 1000 times solid state density deuterium-tritium (DT) plasma, on which a picosecond (ps)-long laser pulse acts,

producing a highly intense relativistic electron beam of 5 MeV electron energy. When this electron beam acts on a volume of solid DT of at least 12 times solid state density, a fusion detonation wave is generated in this volume, in which ten thousand times more energy is produced than laser energy is consumed, according to theoretical estimates without further numerical data or implementation known from experimentation.

The need for very high energy yields consists in the fact that with pulsed operation in a fusion power plant that operates using lasers, fusion energy up to the gigajoule range ( $\text{GJ} = 278 \text{ kWh}$ ) or higher per reaction per second is generated if at all possible, for reasons of cost. It should be noted that the shock effect caused by the pulse of the nuclear reaction is about 3000 times lower than that of a chemical explosion. In this connection, fusion yields obtained with laser pulses of up to 100 kJ of energy and ps duration as in the system of Nuckolls and Wood [13] are of interest. This is different from all other laser-fusion arrangements with yields below 500.

Also of particular interest is the fusion reaction of the hydrogen nuclei (H, protons p) with the boron isotope 11, which is referred to as the HB11 reaction. Each HB11 reaction produces three helium nuclei (alpha particles) with an energy gain of 8.9 MeV. This energy can be converted into heat or electrical energy. The HB11 reaction offers particular advantages in terms of high energy yield, avoiding the radiation problems of D-T fusion and a virtually inexhaustible availability of raw materials. And the HB11 reaction generates less radioactivity per unit of energy produced than the burning of coal, so radioactivity is no problem and can be disregarded.

The combination of laser nuclear fusion with magnetic fields is well known, although with the existing magnetic fields below 100 tesla, yields of less than 100 must be expected. The laser effect on solid state density fusion fuel using laser pulses of around ps duration or less is used for generating a cylindrical reaction zone, for which fusion is obtained only with said low yields. The use of magnetic fields was originally introduced in order to curb cylindrical radial losses, after the ps laser pulses for initiating a fusion flame by igniting an ultrahigh accelerated plasma by the nonlinear force of an extended plane geometry had to be restricted to a limited range of interaction – in contrast to the Nuckolls-Wood process – and the geometry was to extend in a cylindrical area under the interaction cross section, avoiding radial losses. These lateral losses could alternatively be eliminated by using a spherical geometry, as was published. In that case, for the reaction of boron isotope 11 with light hydrogen (HB11) in solid state density, only a maximum of all the fuel in the sphere could supply energy, wherein, as in other cases, the yield was limited and exawatt (EW) laser pulses were necessary.

It is known, in particular, to initiate the HB11 reaction by laser irradiation of a fusion fuel. With laser-based nuclear fusion, originally thermal processes involving an extremely rapid heating of targets at very high thermal pressures for the thermal ignition of fusion reactions were proposed. Using the most powerful lasers in the world, such as those at Livermore (California, USA), laser pulses with a duration of nanoseconds (ns) achieve yields close to breakthrough for a fusion reactor with DT.



Furthermore, departing from thermal methods, it has been found that laser energy can be converted directly into mechanical plasma motion, thereby avoiding complicated heating processes, radiation, instabilities and delayed thermal transitions of electrons to the pressure-generating plasma ions (block ignition). This concept is derived from the ponderomotive force, discovered by Kelvin, by which electrically uncharged bodies can be moved by means of electric fields, and the qualification thereof as a non-linear force which is based on the generation of high-frequency electric fields, wherein the optical properties of plasmas had to be generalized by means of Maxwell's stress tensor [3].

Based on measurements of the laser-plasma interaction, non-linear force was introduced on the basis of the optical properties of the high temperature plasmas generated by lasers in the irradiation of materials, with application to ordinary and relativistic self-focusing and plasma motion [1]. However, it was determined [2] that in order to ignite a fusion reaction of deuterium and tritium, an energy flux density of 100 million joules per square centimeter would be required within a time of one picosecond (ps), which could not be achieved using the laser sources available for practical use during the 1970's.

In 1978, plasma hydrodynamic simulations demonstrated how laser pulses of 1.5 ps duration and a realistic intensity at that time of  $10^{18}$  W/cm<sup>2</sup> could accelerate a 20 wavelength thick layer of deuterium plasma to velocities of  $10^9$  cm/s [3]. These were ultrahigh accelerations of more than  $10^{20}$  cm/s<sup>2</sup>, such as those that were required for the ignition process described in [2]. Confirmation of these ultrahigh accelerations through experimentation was possible only after the introduction of the CPA method (chirped

pulse amplification) for generating ultrashort laser pulses [4]. Since that time, laser intensity (without self-focusing) has increased by ten million times. In ps laser pulses or even shorter laser pulses, the measured power reaches 10 PW (petawatt). With ultrashort laser pulses, the acceleration of plasma blocks in the range of  $2 \times 10^{20} \text{ cm/s}^2$  was directly visibly measured with a Doppler shift of spectral lines [5], which corresponded to theoretical simulations [3], [6]. In a summary of these results [7], it was found that when hydrogen-boron (HB11) is used as a fusion fuel instead of D-T, the thresholds for laser ignition were about the same. That came as a big surprise and was possible only because the ps laser pulses according to [4] provided the non-thermal direct conversion of laser energy to fusion, as opposed to the thermally compressive ignition achieved with ns laser pulses.

These computations for HB11 took into account only the binary reactions as in the computations for the D-T reaction. The HB11 reaction, however, produces a secondary reaction following the primary reaction, by elastic collisions of the resulting alpha particles with boron nuclei, causing an avalanche process with much higher reaction yields than with D-T. Furthermore, in the mentioned processes according to Chu [2], reactions in plane geometry were expected. For a fusion reactor, however the lateral losses must be considered. The simplest solution is to use spherical geometry. If solid state density fusion fuel is used, however, it is found for both DT and HB11 that for energy yields of up to 100, the necessary power of the radiated laser pulses lies not in the range of petawatts but in the thousands of times higher exawatt range [8], which can be achieved using current high performance laser sources. In [8], a nuclear fusion reactor is proposed, which has negligible radioactivity by laser-driven plasma block

ignition of solid state density or moderately compressed fuel, in which the lateral limitation of the reaction is achieved by using magnetic fields and/or a cladding that has a high atomic weight.

5 For the block ignition of nuclear fusion with ps-PW laser pulses [4], it is known that the ultrahigh plasma acceleration by non-linear force [3] calculated in 1978 was measured by Sauerbrey [5] in precise conformity [6], and those for initiation of a fusion flame [2] were reproduced with the same threshold values for energy flux density for D-T fusion. The same high energy flux densities were obtained for HB11 fusion [7],  
10 solely for binary reactions as for DT. The use of classic magnetic fields with cylindrical geometry up to nearly 100 tesla [8] was found to be insufficient for reducing the lateral losses from the reaction. For spherical geometry it was found that yields of only about 100 were achieved for HB11 reactions using at least exawatt laser pulses, even when in addition to the binary reactions the avalanche multiplication was included [9], [10].

15

In [12], a laser-based nuclear fusion reaction is described, in which fusion fuel in the form of capsules is held with a magnetic field strength of 350 tesla. The nuclear fusion reaction is thermal, with laser pulses with a duration in the ns range being used.

## 20 Object of the Invention

An object of the invention is to provide an improved method for generating electrical energy by nuclear fusion which avoids the drawbacks and limitations of conventional methods and which is characterized in particular by an increased energy yield and

simplified implementation in practice. Another object of the invention is to provide an improved nuclear fusion reactor, with which the drawbacks and limitations of conventional techniques can be avoided, and which is characterized in particular by a simplified, practically implementable structure.

5

#### Summary of the Invention

These objects are achieved by a method for generating electrical energy and a nuclear fusion reactor having the features of the independent claims. Advantageous  
10 embodiments and uses of the invention result from the dependent claims.

According to a first broad aspect of the invention, the above object is achieved by a method for generating electrical energy by means of inertial nuclear fusion (inertial confinement fusion) in which a fusion fuel, preferably comprising hydrogen and boron  
15 11, is held within a magnetic field in a cylindrical reaction chamber, and a nuclear fusion reaction is initiated in the fusion fuel by using fusion laser pulses (also referred to as block fusion laser pulses), the pulse duration of which is less than 10 ps and the power of which is more than 1 petawatt. The energy released during nuclear fusion from the nuclei that are produced is converted into electrical energy. According to the  
20 invention, the magnetic field has a field strength which is greater than or equal to 1 kilotesla. The nuclear fusion preferably produces an energy yield of more than 500, in particular more than 1000 per laser energy of the fusion laser pulses used to initiate the fusion flame. The term fusion flame refers to the fusion reaction by picosecond initiation with block ignition (as distinguished from thermal fusion detonation).

According to a second general aspect of the invention, the above object is achieved by a nuclear fusion reactor, which is configured for generating electrical energy, and a magnetic field device which is configured for holding fusion fuel and for generating a magnetic field in a cylindrical reaction chamber, a fusion laser pulse source, configured for emitting fusion laser pulses having a pulse duration of less than 10 ps and a power of more than 1 petawatt and for initiating nuclear fusion in the fusion fuel, and an energy conversion device, which is provided for converting the energy released in the nuclear fusion reaction from the nuclei that are produced into power plant power. The magnetic field device is preferably configured to hold the fusion fuel by means of electrically insulating fibers, e.g. made of quartz. According to the invention, the magnetic field device is configured for generating the magnetic field with a field strength that is greater than or equal to 1 kT.

According to the invention, magnetic fields having a field strength of equal to or greater than kilotesla are preferably used, with the fields more preferably being controlled by a laser-controlled discharge. Advantageously, with the magnetic fields used according to the invention, for the first time the radial losses from a magnetic cylindrical reaction chamber of HB11 with consecutive reactions are prevented such that high yields particularly of greater than 1000 and much more are achieved, with the ps laser pulses having a particularly preferred power of at least 10 PW. The inventors have found that the magnetic fields are suitable for reliably containing the expansion of the reaction volume during ignition of the nuclear fusion.

The invention offers the advantage of providing, for the first time, a realistic and economically feasible realization of a fusion-based, practically inexhaustible and inexpensive energy source. The nuclear fusion reactor according to the invention is a fusion power plant for practical use. The invention provides highly efficient laser  
5 nuclear fusion with magnetic channeling, in which laser-powered nuclear fusion is achieved with yields greater than 500 by applying extremely high magnetic fields.

Advantageously, the ultrahigh magnetic fields [11] of greater than one kilotesla, previously known in only one case, are used, as compared with conventional methods  
10 for generating a more than thirty times higher magnetic field, however instead of fusion which is thermally driven in nanoseconds, a non-thermal block ignition achieved with picosecond pulses is used. In dramatic contrast to all previous methods and configurations, this method enables energy yields to be achieved which lead to the realization of economically operated power plants with overall negligible nuclear  
15 radiation.

According to preferred embodiments of the invention, the fusion fuel has at least one of the following features. According to a first variant, the fusion fuel preferably has a solid state density of up to 20 times the compression as compared with uncompressed  
20 fuel, similar to the case of "fast ignition" according to Nuckolls et al. [13]. According to a further variant, the fusion fuel preferably consists of  $^{11}\text{B}$  isotopes with up to a 15% deviation of light hydrogen in terms of stoichiometry. According to a further variant, the fusion fuel preferably consists of a mixture of light hydrogen and boron, each in at least a 20% atomic concentration.

If, according to a further advantageous embodiment of the invention, the energy of the nuclei generated is captured by electrostatic fields, further advantages in terms of energy yield are achieved. The fusion energy can be converted directly into electrical energy. Preferably, the kinetic energy of the alpha particles produced is converted  
5 directly into electrical energy.

To generate the electrostatic fields, the reaction chamber, more particularly the magnetic field device for forming the reaction chamber, is preferably surrounded by the energy conversion device, the reaction chamber having a negative high voltage relative  
10 to the energy conversion device. For this purpose, the reaction chamber, in particular the magnetic field device, is preferably connected to a high voltage source for generating a negative high voltage relative to the energy conversion device. Particularly preferably, the negative high voltage is at least 1 MV.

15 If, according to a further variant of the invention, the energy conversion device is at ground potential, advantages with respect to the configuration of the nuclear fusion reactor and the feeding thereof with fusion fuel are achieved. The energy conversion device is preferably in the form of a spherical, electrically conductive enclosure  
20 (housing) around the reaction chamber, in particular the magnetic field. Advantageously, the energy conversion device is thereby optimally adapted to the fusion geometry.

Particularly preferably, between the energy conversion device and the reaction chamber a Faraday cage is provided for shielding the static high voltage field from the reaction processes, preventing any penetration of the high-voltage field into the fusion reaction volume.

5

The magnetic field having a field strength of greater than or equal to 1 kilotesla can be realized by any available method for generating strong magnetic fields. According to a particularly preferred embodiment of the invention, the magnetic field is generated by means of an interaction with discharge laser radiation by a discharge current in electrodes which are coupled via at least one coil, in particular a single coil winding.

10

The magnetic field device of the nuclear fusion reactor preferably has a pair of electrodes, two coils and a magnetic field pulsed laser source, which is provided for irradiating the electrodes with discharge laser radiation. Preferably, the magnetic field device is configured to hold the fusion fuel by means of electrically insulating fibers, z.

15

B. made of quartz, on the coils or other support elements of the magnetic field device. Particularly preferably, the magnetic field device is implemented with the configuration described in [11] by S. Fujioka, et al. The discharge laser radiation preferably comprises laser pulses (hereinafter: magnetic field generating laser pulses or magnetic field laser pulses) having a pulse duration of less than 20 ns and energy of more than 100 J.

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Advantageously, according to a further embodiment of the invention, the magnetic field can be intensified by designing the electrodes for generating the magnetic field to comprise two plates spaced from one another, between which a magnetic field laser pulse absorbing material is arranged, the form of which is adapted to a Rayleigh profile



of generated plasma. The material particularly preferably comprises a foam material, such as polyethylene, and the bi-Rayleigh profile of electron density according to Fig. 10.17 of [3] is selected.

- 5 According to a further, particularly advantageous embodiment of the invention, block ignition is initiated by the fusion laser pulses. For this purpose, the fusion laser pulses preferably have a duration of less than 5 ps and/or a power of at least 1 petawatt. The fusion pulsed laser source for generating the fusion laser pulses having a duration of less than 5 ps preferably comprises the same type of source as the 10 PW-ps laser  
10 assembly known from the Institute of Laser Engineering at Osaka University.

- The fusion laser pulses preferably have a contrast ratio of at least  $10^6$ . To achieve this, advance pulses are particularly preferably suppressed up to a time of less than 5 picoseconds before the arrival of a (main) fusion laser pulse at the fusion fuel.  
15 Furthermore, benefits in terms of triggering the fusion reaction result when the fusion laser pulses have an intensity of at least  $10^{17}$  watts per square centimeter upon arrival at the fusion fuel.

- According to a further advantageous embodiment of the invention, the fusion fuel is  
20 partially or fully encapsulated by a cover layer, particularly on the side of laser-plasma interaction, the cover layer being made of a material which has an atomic weight of greater than 100. The pulse transmission for generating the fusion flame in the reaction fuel is advantageously increased as a result. The cover layer preferably has a thickness equal to or less than 5 microns, and/or it may be formed by vapor deposition.

### Brief Description of the Figures

Further details and advantages of the invention will be explained below with reference  
5 to the accompanying drawings. Shown are:

Figure 1: a schematic illustration of one embodiment of the nuclear fusion reactor of  
the invention;

10 Figure 2: a schematic illustration of the irradiation of a magnetic field device with  
magnetic field pulses and fusion laser pulses; and

Figure 3: further details of one embodiment of the nuclear fusion reactor of the  
invention.

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### Preferred Embodiments of the Invention

Features of preferred embodiments of the invention are described below primarily with  
reference to the generation of the magnetic field for holding the fusion fuel and the  
20 design of the energy conversion device. Details of the invention, such as the details of  
laser pulse sources, the physical principles of the HB11 reaction, the connection of the  
fusion reactor to other components of a power plant, in particular for preparing and  
delivering the fusion fuel, for controlling the fusion reactor, for protecting the  
environment against thermal effects and/or electric fields, are not described, as these

can be realized by a person skilled in the art based on his/her knowledge of known fusion and plasma physics and conventional power plant engineering, depending on the specific conditions of use of the invention. Reference is made by way of example to a fusion reactor having a single reaction chamber. However, the invention is not limited to this design. Rather, a fusion reactor may be equipped with a plurality of reaction chambers, each having a magnetic field device for holding fusion fuel. The reaction chambers may be operated alternatingly in sequence so as to enable a continuous or quasi-continuous generation of electrical energy.

Figure 1 shows a schematic illustration of one embodiment of the nuclear fusion reactor 100 of the invention, which comprises a magnetic field device 10 for holding a fusion fuel 1 with a magnetic field in a cylindrical reaction chamber 2, a magnetic field pulsed laser source 20 for emitting magnetic field laser pulses 3 (or: magnetic field generating laser pulses), a fusion pulsed laser source 30 for emitting fusion laser pulses 4 (or: block fusion laser pulses) and an energy conversion device 40 for converting the energy that is released from the nuclei that are produced during nuclear fusion.

The magnetic field device 10 for generating a magnetic field having a strength of e.g. 4.5 kT in reaction chamber 2 comprises two parallel metal plates 11, 12 made of nickel, for example, and having a thickness of e.g. 2 mm and a characteristic expansion of e.g. 3 cm. The metal plates 11, 12 are connected to one another via electrical conductors, which form two windings 13 of a coil. One of the metal plates 11 has an opening 14 through which the magnetic field laser pulse 3 is beamed with a duration of, for example, 1 ns to 2 ns, and e.g. 10 kJ of energy. The plasma produced by each magnetic

field laser pulse 3 generates a current surge in the windings 13 with a magnetic field having a volume of a few cubic millimeters and several ns duration.

Opening 14 is a circular opening in the upper metal plate 11 in Figure 1. The diameter and optionally also the geometric shape of opening 14 are selected based on the properties, in particular the intensity, the diameter and the profile, of the magnetic field laser pulses 3. The diameter of opening 14 is 5 mm, for example. Rather than the circular shape, an elliptical shape may also be provided. Opening 14 may be optimized with a view to maximizing the magnetic field for a maximum fusion yield.

The second metal plate 12, which faces opening 14, can be provided with an absorption layer which serves to reduce the optical reflection of the magnetic field laser pulses 3 and to increase the dielectric properties of the capacitor formed by the metal plates 11. The absorption layer (not shown) is preferably disposed over the entire surface of the metal plate 12, and is more preferably made of a foam material, for example polyethylene. The foam material is selected such that after laser irradiation, an electron density distribution is formed as a bi-Rayleigh profile.

The magnetic field laser pulses 3 are generated by the schematically illustrated magnetic field pulsed laser source 20, which contains, for example, a Nd-YAG laser and other optical components (not shown) for directing the magnetic field laser pulses 3 toward the magnetic field device 10. The duration of the magnetic field laser pulses 3 may optionally be shortened by a time in the nanosecond range by using an iodine laser having a pulse length of 100 ps, and/or with shorter laser pulses following a CPA

power increase. The magnetic field generated by the magnetic field device 10 can thereby be advantageously intensified.

The fusion pulsed laser source 30 is configured to generate the fusion laser pulses 4 with a duration of less than 5 ps and an intensity in excess of  $10^{19}$  W/cm<sup>2</sup>. The fusion laser pulses 4 preferably have a contrast ratio of at least  $10^6$  for the duration of less than 5 ps prior to the arrival of the fusion laser pulses 4 at fusion fuel 1. In addition, the fusion laser pulses 4 preferably have an intensity distribution with less than 5% fluctuation over the beam cross section, except in an outer 5% border region of the beam cross section. The block ignition of the fusion reaction in fusion fuel 1 is thereby advantageously optimized. This intensity distribution is achieved, for example, by a fusion pulsed laser source 30 which has a bundle of fiber amplifiers, each individual fiber having a single mode emission. The fusion pulsed laser source 30 further contains a pulsed laser, such as a solid state pulsed laser, for generating ps laser pulses.

The magnetic field pulsed laser source 20 and the fusion pulsed laser source 30 are coupled to a control unit 50. Control unit 50 is configured such that the magnetic field laser pulses 3 and the fusion laser pulses 4 are synchronized with one another. In reaction chamber 2, the maximum magnetic field is generated immediately before each fusion laser pulse 4 arrives at fusion fuel 1.

Fusion fuel 1 is a solid state, cylindrical body, based on HB11, for example, and having a length of 1 cm and a diameter of 0.2 mm. The surface of fusion fuel 1 has a cover layer over the laser interaction surface which has a thickness of three laser vacuum

wavelengths. The top cover layer consists of elements having an atomic weight greater than 100, for example, silver. The cover layer improves pulse transmission for generating the fusion flame in fusion fuel 1. Fusion fuel 1 is held in the magnetic field device by means of quartz fibers.

5

Energy conversion device 40 generally comprises an electrically conductive component (indicated schematically by dashed lines in Figure 1; see also Figure 3), which surrounds magnetic field device 10 on all sides. Magnetic field device 10 is supported inside energy conversion device 40 (support not shown in Figure 1; see, for example, support bar 44 in Figure 3). Energy conversion device 40 is preferably connected to ground potential, while a negative high voltage, for example -1.4 MV, is applied to magnetic field device 10 by means of a voltage source 15. Energy conversion device 40 is configured to capture high-energy He nuclei (alpha particles) released during the fusion reaction of fusion fuel 1, and convert them by means of high voltage direct current transmission (HVDC) [16] into a discharge current. The discharge current supplies the electrical energy into which the energy released in the fusion reaction is converted.

15

The arrival of the magnetic field laser pulses 3 and fusion laser pulses 4 at the reaction unit formed by magnetic field device 10, is also illustrated in Figure 2. Magnetic field device 10 is configured as described above in reference to Figure 1. The magnetic field generating laser pulses 3 generate a magnetic field having a field strength of 10 kT, for example. Fusion fuel 1 is placed (and held in place by the quartz fibers) within axis 1 of reaction chamber 2, which is the same as the axis of the magnetic field, and is acted

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on by a magnetic field within a time range of nanoseconds. During the period in which the magnetic field is generated, a block ignition is generated in fusion fuel 1 by means of fusion laser pulse 4. Fusion laser pulse 4 has an energy of 30 kJ, for example (equivalent to 30 PW power), so that the products of the nuclear fusion (helium nuclei) have an energy output of about 1 GJ. This energy is converted electrostatically by energy conversion device 40, with low heat loss, into electric power (1 GJ is equivalent to around 280 kWh). This advantageously enables fusion reactor 100 to economically supply a high electric current, even at a low reaction rate of one reaction per second. The fusion reaction destroys magnetic field device 10 by the action of the fusion products, so that for the subsequent fusion reaction, another magnetic field device 10 loaded with fusion fuel must be supplied.

In contrast to the diagrams in Figures 1 and 2, the direction of incidence of the magnetic field generating laser pulses 3 can be rotated by an angle of up to  $80^\circ$  between the vertical incidence in the plane spanned by the vertical direction of incidence and the normal plane of the magnetic field, with rotation occurring in the plane which is oriented parallel to the coils 13.

Further details of an embodiment of the nuclear fusion reactor 100 according to the invention are shown in Figure 3. In this embodiment of the invention, energy conversion device 40 comprises an electrically conductive sphere, at the center of which magnetic field device 10 of Figures 1 and 2 is arranged. Energy conversion device 40 is made, for example, of stainless steel having a thickness of 10 mm and a diameter of at least 1 m. The spherical outer vessel of the reactor must be large enough and its walls

must be thick enough to withstand the mechanical shock of the fusion reaction. This results in the advantage that the mechanical pressure amounts to the root of the energy of the nuclear reaction divided by the energy produced in chemical reactions, which is a factor of approximately 3000. The shock on the wall of the sphere transferred by the pulse of the total of generated alpha particles is then equivalent to the explosion of approximately 5 grams of TNT.

In a practical embodiment of the invention, all components of fusion reactor 100 are formed with rounded surfaces, which are free of corners and edges. A field emission of electrons and the formation of dark discharges is thereby advantageously avoided. The entire assembly is located under a high vacuum generated by vacuum pumps (not shown).

The spherical surface of energy conversion device 40 has a plurality of windows, which comprise a first window 41 for beaming in the magnetic field laser pulses 3, a second window 42 for beaming in the fusion laser pulses 4 and a third window 43 for loading the energy conversion device 40 with the magnetic field device 10 and the fusion fuel 1. Since the interior of energy conversion device 40 is evacuated, the first windows 41 and second windows 42 are formed by pressure-tight, transparent panes, for example, of glass. The third window 43 is open and coupled in a pressure tight connection to an adjacent container, and is used for supplying and supporting the central magnetic field device 10 (reaction unit). This is provided on a rod-shaped fuel carrier 44, which is loaded outside of the energy conversion device 40 with fusion fuel 1, and is inserted and positioned at the center of the sphere, particularly freely floating. Fuel carrier 44



and magnetic field device 10 are located, at a potential of -1.4 MV relative to energy conversion device 40, at ground potential. Fuel carrier 44 is in the form, for example, of a rod with a length of at least one-half the diameter of energy conversion device 40.

5     Inside energy conversion device 40, a spherical or otherwise shaped, e.g. irregularly shaped, Faraday cage 45, is provided, which encloses magnetic field device 10. The Faraday cage 45, e.g. in the form of a mesh or grid, is designed to prevent the static high-current field from influencing the processes involved in generating the magnetic field of the magnetic field device. The energy conversion device 40 is shielded on all  
10    sides by the Faraday cage 45. Fuel carrier 44 with magnetic field device 10 and fusion fuel 1 at the electrical potential of 1.4 MV comes from the adjoining container, which is located electrically insulated in the same vacuum as the interior of the spherical energy conversion device 40, so that after each reaction, additional reactor units are brought into the center of the energy conversion device 40 at the same potential. Access  
15    to the interior for the loading units of the reaction is provided through air locks.

During continuous operation, magnetic field devices 10, loaded with fusion fuel 1, are introduced repeatedly in succession into energy conversion device 40, exposed to the magnetic field generating laser pulses for generating the magnetic field, and during  
20    generation of the magnetic field are exposed to the block fusion laser pulses for block fusion, and are then replaced by a new magnetic field device 10 loaded with fusion fuel 1.

The double charged alpha particles of the same energy (helium nuclei) generated with each fusion reaction reach the spherical energy conversion device 40 through the mesh of the Faraday cage 45 and release their kinetic energy to the energy conversion device 40. At the potential of -1.4 MV the energy of the alpha particles is available, and at a charge -1.4 MV the energy is supplied as a seconds long discharge current of 714 Amperes by means of the high voltage direct current transmission technique known from [16]. The high voltage direct current is converted into conventional three-phase alternating current in a known manner, as in HVDC technology [16].

10 The same energy of all alpha particles of 2.9 MeV generated in the fusion process is widened by a secondary avalanche reaction to a spectrum of both higher and lower energies, thereby advantageously improving the energy yield of energy conversion by a few percent more.

15 Refilling for a subsequent reaction at the potential of -1.4 million volts can then be accomplished within only seconds with the prepared fixation of the adjustment of the laser pulses toward the central reaction unit of Figure 2. Before it is introduced into the reactor sphere (energy conversion device 40), the remains from the preceding reaction can be removed. The cost of each new unit including the HB11 fusion fuel can be held to a fraction of the overhead costs of the generated electrical energy.

20

The features of the invention disclosed in the foregoing description, the drawings and the claims, taken alone, in combination or in sub-combinations, are considered essential to implementing the various embodiments of the invention.

## CLAIMS

1. A method for generating electrical energy, comprising the steps of

- providing a fusion fuel (1), the fusion fuel (1) being held in a magnetic field within a

5 cylindrical reaction chamber (2),

- initiating nuclear fusion in the fusion fuel (1), in which fusion laser pulses (4) having a pulse duration of less than 10 ps and power of more than 1 petawatt are used to generate a fusion flame, and

- converting the energy that is released during the nuclear fusion from the nuclei that  
10 are produced into power plant power,

**characterized in that**

- the magnetic field has a field strength which is greater than or equal to 1 kilotesla, and

- the nuclear fusion has an energy yield of more than 500 per laser energy of the fusion laser pulses (4) used to initiate the fusion flame.

15

2. The method according to claim 1, in which the fusion fuel (1) has at least one of the following features:

- the fusion fuel (1) has a solid state density of up to 20x compression,

- the fusion fuel (1) consists of 11B isotopes with up to 15% deviation of light hydrogen

20 in terms of stoichiometry,

- the fusion fuel (1) consists of a mixture of light hydrogen and boron, each in an atomic concentration of at least 20%.

3. The method according to any of the preceding claims, in which

- the energy of the nuclei that are produced is captured in the highest possible percentage by electrostatic fields.

4. The method according to any of the preceding claims, in which

- 5 - the reaction chamber (2) is surrounded by an energy conversion device (40), and  
- the reaction chamber (2) has a negative high voltage relative to the energy conversion device (40).

5. The method according to claim 4, in which

- 10 - the energy conversion device (40) is at ground potential,  
- the energy conversion device (40) forms a spherical, electrically conductive enclosure of the reaction chamber (2),  
- between the energy conversion device (40) and the reaction chamber (2) a Faraday cage is provided for shielding the static high voltage field from the reaction processes,  
15 and/or  
- the negative high voltage of the reaction chamber (2) relative to the energy conversion device (40) is at least 1 MV.

6. The method according to any of the preceding claims, in which

- 20 - the magnetic field is generated by a discharge current in electrodes that are coupled to coils (13), by means of an interaction with magnetic field generating laser pulses (3).

7. The method according to claim 6, in which

- the magnetic field laser pulses (3) are laser pulses having a pulse duration of less than 20 ns and energy of more than 100 J.

8. The method according to either of claims 6 and 7, in which

5 - the magnetic field laser pulses (3) have a direction of incidence with respect to the magnetic field generating assembly, wherein the direction of incidence deviates up to  $80^\circ$  from vertical within a plane oriented parallel to the coils (13).

9. The method according to any of claims 6 to 8, in which

10 - the electrodes for generating the magnetic field comprise two plates (11, 12) spaced from one another, between which a field intensifying material is arranged, in a shape that is adapted to a Rayleigh profile of a generated plasma.

10. The method according to any of the preceding claims, in which

15 - a block ignition is initiated by means of the fusion laser pulses (4).

11. The method according to claim 10, in which

- the block ignition is initiated by fusion laser pulses (4) of less than 5 ps duration.

20 12. The method according to any of the preceding claims, in which

- the fusion laser pulses (4) have a contrast ratio of at least  $10^6$ , and/or

- the fusion laser pulses (4) have an intensity of at least  $10^{17}$  watts per square centimeter.

13. The method according to any of the preceding claims, in which

- the fusion fuel (1) has a cover layer made of a material which has an atomic weight greater than 100.

14. The method according to claim 13, in which

- 5    - the cover layer has a thickness equal to or less than 5 microns, and/or  
      - the cover layer is produced by vapor deposition.

15. A nuclear fusion reactor configured for generating electrical energy, comprising

- 10   - a magnetic field device (10), which is configured to hold a fusion fuel (1) and to generate a magnetic field in a cylindrical reaction chamber (2), and  
      - a fusion pulsed laser source (30), which is configured to emit fusion laser pulses (4) having a pulse duration of less than 10 ps and power of more than 1 petawatt and to initiate a nuclear fusion reaction in the fusion fuel (1), wherein  
      - an energy conversion device (40) is provided for converting the energy that is released during the nuclear fusion from the nuclei that are produced into power plant power,  
      **characterized in that**  
      - the magnetic field device (10) is configured to generate the magnetic field at a field strength of greater than or equal to 1 kT.

20

16. The nuclear fusion reactor according to claim 15, in which

- the magnetic field device (10) with the reaction chamber (2) is surrounded by the energy conversion device (40), wherein

- the magnetic field device (10) is connected to a voltage source (15) for generating a negative high voltage relative to the energy conversion device (40).

17. The nuclear fusion reactor according to claim 16, in which

- 5     - the energy conversion device (40) is at ground potential,
- the energy conversion device (40) forms a spherical, electrically conductive enclosure for the magnetic field device (10),
- between the energy conversion device (40) and the reaction chamber (2), a Faraday cage is provided for shielding the static high voltage field from the reaction processes,
- 10    and/or
- the voltage source is configured for generating the negative high voltage in an amount of at least 1 MV.

18. The nuclear fusion reactor according to any of claims 15 to 17, in which the

15    magnetic field device (10) comprises

- a pair of electrodes (11, 12) which are coupled to coils (13), and
- a magnetic field pulsed laser source (20), which is positioned for irradiating the electrodes with magnetic field laser pulses (3), wherein
- the magnetic field can be generated by a discharge current in the electrodes (11, 12)
- 20    and coils (13) by means of an interaction with the magnetic field laser pulses (3).

19. The nuclear fusion reactor according to claim 18, in which

- the magnetic field pulsed laser source (20) is configured for generating the magnetic field laser pulses (3) in the form of laser pulses having a pulse duration of less than 20 ns and energy of more than 100 J.

5      20.      The nuclear fusion reactor according to claim 18 or 19, in which

- the magnetic field pulsed laser source (20) is positioned such that the magnetic field laser pulses (3) have a direction of incidence with respect to the magnetic field generating assembly, wherein the direction of incidence deviates up to 80° from vertical within a plane oriented parallel to the coils (13).

10

21.      The nuclear fusion reactor according to any of claims 18 to 20, in which

- the electrodes of the magnetic field device (10) comprise two plates (11, 12) spaced from one another, between which a field intensifying material is arranged in a shape which is adapted to a Rayleigh profile of the generated plasma.

15

22.      The nuclear fusion reactor according to any of claims 18 to 21, in which

- the fusion pulsed laser source (30) is configured for generating the fusion laser pulses (4), the duration of which is less than 5 ps.

20      23.      The nuclear fusion reactor according any of claims 18 to 22, in which the fusion pulsed laser source (30) is positioned such that

- the fusion laser pulses (4) have a contrast ratio of at least  $10^6$ , and/or

- the fusion laser pulses (4) have an intensity of at least  $10^{17}$  watts per square centimeter.

ABSTRACT



## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2014/003281

## A. CLASSIFICATION OF SUBJECT MATTER

INV. G21B3/00 G21B1/03 G21B1/23  
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G21B

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

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

EPO-Internal, WPI Data, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	<p>GOTCHEV O ET AL: "Seeding magnetic fields for laser-driven flux compression in high-energy-density plasmas", REVIEW OF SCIENTIFIC INSTRUMENTS, AIP, MELVILLE, NY, US, vol. 80, no. 4, 14 April 2009 (2009-04-14), pages 43504-43504, XP012128204, ISSN: 0034-6748, DOI: 10.1063/1.3115983 the whole document</p> <p>----- -/--</p>	<p>1-7, 10-12, 15-19, 22,23</p>



Further documents are listed in the continuation of Box C.



See patent family annex.

\* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

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## INTERNATIONAL SEARCH REPORT

International application No

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	S. FUJIOKA ET AL.: "Kilotesla magnetic field due to a capacitor-coil target driven by high power laser", SCIENTIFIC REPORTS, vol. 3, 30 January 2013 (2013-01-30), pages 1-7, XP002737004, DOI: 10.1038/srep01170 page 1, paragraph 1 - paragraph 3 page 6, paragraph 4 - paragraph 6 -----	1-7, 10-12, 15-19, 22,23
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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2014/003281

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DE 102012001634	A1	01-08-2013	NONE
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