Laser and Particle Beams

cambridge.org/lpb

Extreme laser pulses for non-thermal fusion ignition of hydrogen–boron for clean and low-cost energy

Review Article

Cite this article: Hora H, Eliezer S, Miley GH, Wang J, Xu Y, Nissim N (2018). Extreme laser pulses for non-thermal fusion ignition of hydrogen–boron for clean and low-cost energy. *Laser and Particle Beams* **36**, 335–340. https://doi.org/10.1017/S0263034618000289

Received: 7 June 2018
Accepted: 17 July 2018

Key words:
Clean energy; extreme power laser pulses; hydrogen–boron fusion; non-thermal fusion; plasma blocks

Author for correspondence:
Heinrich Hora, University of New South Wales, Sydney 2052, Australia. E-mail: h.hora@UNSW.edu.au

Heinrich Hora[1,2], Shalom Eliezer[3,4], George H. Miley[5], JiaXiang Wang[6], YanXia Xu[6] and Noaz Nissim[3]

[1]University of New South Wales, Sydney 2052, Australia; [2]HB11 Energy Pty. Ltd., Sydney, Australia; [3]Soreq NRC, Yavne, Israel; [4]Polytechnique University, Madrid, Spain; [5]Department of Nuclear Plasma and Radiological Engineering, University of Illinois, Urbana IL, USA and [6]State Key Laboratory of Precision Spectroscopy, Science Building A908a, East China Normal University, Shanghai 200062, China

Abstract

After achieving significant research results on laser-driven boron fusion, the essential facts are presented how the classical very low-energy gains of the initially known thermal ignition conditions for fusion of hydrogen (H) with the boron isotope 11 (HB11 fusion) were bridged by nine orders of magnitudes in agreement with experiments. This is possible under extreme non-thermal equilibrium conditions for ignition by >10 PW-ps laser pulses of extreme power and nonlinear conditions. This low-temperature clean and low-cost fusion energy generation is in crucial contrast to local thermal equilibrium conditions with the advantage to avoid the difficulties of the usual problems with extremely high temperatures.

Introduction

The conversion between different energies (mechanical, electric, chemical or nuclear reaction, thermal, radiation, gravitation, hydro-mechanical) of each one into another follows the principle of the energy conservation in physics. One exception can be by restrictions that thermal energy cannot completely flow on its own to higher temperatures (second law of thermodynamics). The changing of chemical energy per reaction of about electron volt (eV) into mechanic energy by the heat from burning is used since the steam engine or the combustion motor. The processes at local thermal equilibrium (LTE) reduces the efficiency from few to not more than about the range of a dozen of percents at temperatures in the order of 0.1 eV. Without needing heat and combustion, the direct change of chemical energy into electric and then into mechanical energy of motion is possible by batteries or accumulators.

Can this be done with nuclear fusion energy? This was a fundamental question at the Third International Symposium on High Power Laser Science and Technology (HPLST) in a Mini-Worksop by the organizer (Zhou, 2018) in order to demonstrate that pulsed fusion with lasers in plasmas can offer the low-temperature initiation of fusion even at the important high plasma density of about the solid state! This has the advantage to avoid the thermal equilibrium temperature fusion much above 10 million degrees and the unfavorable conditions at extremely low densities at magnetic confinement fusion at more than ten orders of magnitudes lower densities for continuously working reactors like ITER (Bigot, 2017). These developments were fundamental for the special new initiative by the Chinese Academy of Science (Zhang, 2018) for a research program on laser fusion with picoseconds laser pulses at very extreme, ultrahigh power. This is possible now by using the latest developments of picosecond laser pulses for initiation of the ignition of fusion for providing plasma conditions of extreme non-LTE. In addition, it opens for the very first time the fusion of hydrogen with the boron isotope 11 (HB11 fusion) (Hora *et al*., 2015, 2017a). The difference by non-LTE conditions refers also to laser fusion with nanosecond laser pulses (Hurricane *et al*., 2014) where the differing LTE condition arrived at other kinds of respectable results yet below break-even.

The energy of nuclear reactions is in the range of 10 MeV in contrast to the eV of chemical reactions. For thermal equilibrium reactions at LTE processes, higher temperatures of >100 million degrees or >10 keV are needed. These are the temperatures needed for fusion power reactors at conditions of thermal equilibrium in contrast to thermal burning of chemicals. A splendid example is the stellarator reactor. After more than 20 years of experiments for continuous fusion of deuterium D in a stellarator, it was possible to produce the very first DD reactions in the Wendelstein experiment (Grieger and Wendelstein Team 1981), see also Section 2.6 of Hora (1991), where equilibrium temperatures of 800 eV (close to 10 million degrees) were reached and continued to arrive at to considerably higher values with the ITER option (Bigot, 2017).

The following summary about the results for the HB11 fusion with picosecond laser pulses was based on the measured ultrahigh acceleration of plasma blocks using lasers by Sauerbrey (1996). This is possible only based on the most exceptional related measurement by Zang *et al.* (1998) that the picosecond laser pulses had to have a very difficult high contrast ratio such that relativistic self-focusing could be avoided. This was needed for the theory of plasma-block ignition (Hora 1981, 2016; Osman *et al.*, 2004; Hora *et al.*, 2015, 2017a)

Extreme thermal non-equilibrium conditions for boron fusion

The following evaluation to reach the very high-energy gain from laser-driven fusion initiated by ultrahigh power picosecond laser pulses has to be explained, why a change of the HB11 fusion energy gains by nine orders of magnitudes above the classical values was needed. It is easy to understand that bridging such a big gap may be considered as good as impossible. But it has been just measured by laser technology.

The enormous bridging by nine orders of magnitudes is just possible by choosing the non-LTE option of a nearly non-thermal laser fusion based on the non-linear (ponderomotive) force by most extreme laser pulses of picosecond duration (Hora, 1969, 1981) as measured with HB11 fuel (Picciotto *et al.*, 2014; Margarone *et al.*, 2015; Hora, 2015, 2017a).

This can be seen from the equation of motion for the force density **f** in a plasma with the thermokinetic pressure p given by the temperature T and the particle density n, and by Maxwell's stress tensor **M** of the electric and magnetic fields **E** and **H** of the laser with inclusion of the complex refractive index varying dynamically on time and space within the plasma (Hora *et al.*, 2015, 2017a)

$$\mathbf{f} = -\nabla p + \mathbf{f}_{\mathrm{NL}} = -\nabla p - \nabla \cdot M \tag{1}$$

$$\begin{aligned}\mathbf{M} = [&\mathbf{EE} + \mathbf{HH} - 0.5(\mathbf{E}^2 + \mathbf{H}^2)\mathbf{1} \\ &+ (1 + (\partial/\partial t)/\omega)(n^2 - 1)\mathbf{EE}]/(4\pi) \\ &- (\partial/\partial t)\mathbf{E} \times \mathbf{H}/(4\pi c)\end{aligned} \tag{2}$$

with the unity tensor **1**. For plane geometry interaction, the non-linear force $\mathbf{f}_{\mathrm{NL}}$ is for perpendicular irradiated plasma surface

$$\begin{aligned}f_{\mathrm{NL}} &= -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) \\ &= -(\omega_{\mathrm{p}}/\omega)^2(\partial/\partial x)(E_{\mathrm{v}}^2/\mathbf{n})/(16\pi)\end{aligned} \tag{3}$$

using the dielectric constant **n** and the vacuum electric field amplitude E_{v} of the laser. At thermal equilibrium, the easiest fusion reactions of heavy hydrogen H with superheavy hydrogen D (DT fusion) need a temperature of about 100 million degrees and of HB11 fusion needs more than five times higher temperatures

$$D + T =^4 \mathrm{He} + n + 17.4\,\mathrm{MeV} \tag{4}$$

$$\mathrm{H} +^{11} \mathrm{B} = 3^4\mathrm{He} + 8.7\,\mathrm{MeV} \tag{5}$$

where next to the harmless helium ^{4}He, the generated neutrons n cause a problem of radioactivity in the reaction waste. This is primarily fully excluded in the HB11 reaction.

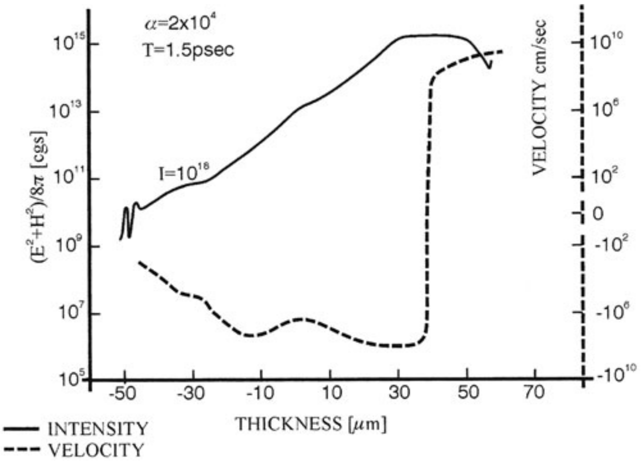

Fig. 1. The 10^{18} W/cm^2 neodymium glass laser intensity in one-dimensional geometry is incident from the right-hand side on an initially 100 eV hot deuterium plasma slab of initially 0.1 mm thickness whose initial density has a very low reflecting bi-Rayleigh profile, resulting in a laser energy density and a velocity distribution from plasma hydrodynamic computations at time $t = 1.5$ ps of interaction. The driving non-linear force is the negative of the energy density gradient of the laser field $(\mathbf{E}^2 + \mathbf{H}^2)/8\pi$. The dynamic development of temperature and density had accelerated the plasma block of about 15 vacuum wave length thickness of the dielectric enlarged skin layer moving against the laser (positive velocity) and another block into the plasma (negative velocity) showing ultrahigh $>10^{20}$ cm/s^2 acceleration of the deuterium plasma block to velocities above 10^9cm/s within the 1.5 ps.

With the aim to minimize heat by using non-LTE or non-equilibrium plasmas, the equation of motion (1) needs such high laser intensities with fields that the non-linear force $\mathbf{f}_{\mathrm{NL}}$ produces much higher pressures than the thermal pressure p. The result of an example calculated in 1977 is shown in Figure 1 (Figs 10.18a&b of Hora 1981 or drawn together in Fig. 8.4 of Hora 2016).

The motion of the plasma bocks after 1.5 ps interaction in Figure 1 can be seen in Figure 2. The ultrahigh acceleration of the plasma block when moving against the laser light were first measured by the blue Doppler shift of the spectral lines by Sauerbrey (1996) using the sub-picosecond laser pulses (Strickland and Mourou, 1995) of the comparable intensities as in Figure 1 in agreement with the numerical calculation of 1977 (Hora, 1981) with reconstructing a dielectric swelling of the laser intensity in the irradiated plasma of a usual value near 3 (Hora *et al.*, 2017a, 2007). This measurement was repeated (Földes *et al.*, 2000) after similar accelerations were measured (Badziak *et al.*, 1999) which were in drastic difference to the measurements with a red Doppler shift. The blue shift was proved to be possible only by using most extreme contrast ratios (Zhang *et al.*, 1998; Danson *et al.*, 2018) of the laser pulse in order to avoid relativistic self-focusing. This was measured in a most sophisticated way by Zhang *et al.* (1998), see Chapter 8.3 of Hora (2016). The red shift happens always at plasma densities lower than critical when instead of the dielectric plasma-block explosion, only ordinary radiation pressure acceleration happens. The red shift was the result of numerous PIC computations where dielectric effects were not included. The first difficult inclusion of densities close to critical densities were successfully demonstrating the dielectric explosion of plasma blocks (Hora *et al.*, 2018) (see Fig. 2).

The discovery of Sauerbrey (1996) of the blue shift on the basis of the measurements by Zhang *et al.* (1998), Badziak *et al.* (1999) and Földes *et al.* (2000) led to the exploring of the picosecond

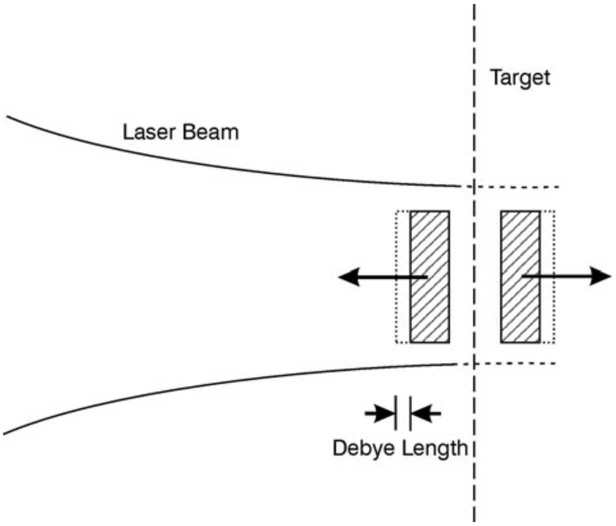

Fig. 2. Schematic representation of skin depth laser interaction where the non-linear force accelerates a plasma block against the laser light and another block toward the target interior. In front of the blocks are electron clouds of the thickness of the effective Debye lengths.

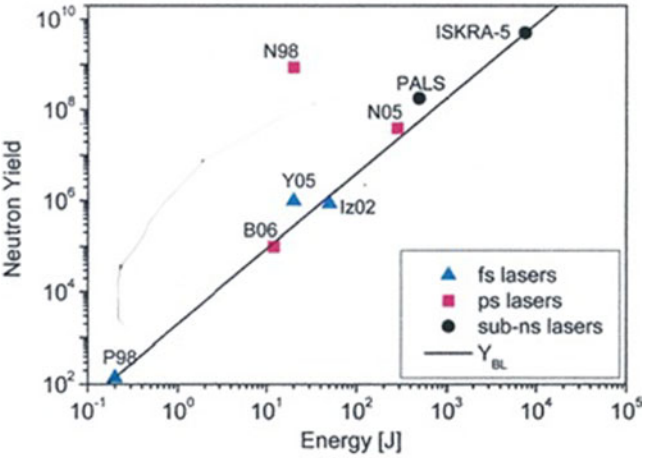

Fig. 3. Measured fusion neutrons emitted from solid targets containing deuterium irradiated by femto to 300 ns laser pulses depending on the energy of the pulses [compiled by Krasa *et al.* (2013)].

initiation of solid density fusion fuel (Hora *et al.*, 2002a, 2002b; Picciotto *et al.*, 2014; Margarone *et al.*, 2015) by updating (Hora, 2009) of the computations by Chu (1972) and Bobin (1974). This was leading to the five orders of magnitudes increased fusion gains of HB11 above the classical values (Hora *et al.*, 2010) and the further four orders increase by the avalanche of the α reaction [Eq. (5)] (Eliezer *et al.*, 2016) for arriving at the results (Hora *et al.*, 2015, 2017a). Only this rather unusual research path led to the design of the basically new type of a clean and low-cost LASER BORON FUSION reactor.

First measurement of low-temperature fusion reactions by laser pulses

Up to 1998, laser fusion was studied mostly by heating of the fuel under conditions of thermal equilibrium. Many measurements were known how the laser interaction with nuclear fusion fuel – mostly with heavy hydrogen (deuterium D) or mixed with superheavy hydrogen (tritium T) – produced nuclear fusion (DT reactions) detected by the measured number of the generated neutrons. The experiments up to the year 1998 were mostly in the way that laser pulses of about nanosecond duration heated and compressed the fuel under thermal equilibrium. These reactions arrived now at the NIF-experiment in Livermore/California nearly at break-even but where the generated energy is still lower than the input laser energy but reached respectable values. These experiments are based on the conditions of LTE (Hurricane *et al.*, 2014).

Apart from these studies with plasmas at LTE conditions, a most exceptional experiment was in 1998 by Norreys *et al.* (1998) irradiating deuterated targets, and to apply similar shorter than picosecond laser pulses as by Sauerbrey (1996). Compared with very many usually laser-driven experiments, suddenly, the number of fusion neutrons (Krasa *et al.*, 2013), there was a neutron gain nearly four orders of magnitudes higher than under the known heating conditions (Fig. 3, see N98). It was clearly confirmed that the interaction area had a very low temperature exactly showing the conditions of non-LTE. In retrospect with what we know today, this was a typical non-linear force-driven plasma-block fusion (Hora, 1969; Hora *et al.*, 2015, 2017a). At different conditions when irradiating sandwich targets for thermally dominated reactions (NO5 of Fig. 3), the measured fusion neutrons were going down to the values in full agreement with all the large number of measured usual fusion gains at thermal equilibrium.

The understanding of the four orders of magnitudes increased fusion gains without much heating is given by the force density in the plasma in the presence of the very high laser intensity. The thermokinetic pressure p can be only a small perturbation against the pressure due to non-linear force by the laser electric and magnetic fields $\mathbf{E}$ and $\mathbf{H}$ with a much higher energy density $(\mathbf{E}^2+\mathbf{H}^2)/(8\pi)$ as in the case of Figure 1, where a first interpretation of a non-LTE, non-linear, force-dominated, low-temperature fusion was elaborated before (Hora *et al.*, 2002a). This is now endorsed in convincing details by the results of laser boron fusion (Hora *et al.*, 2015, 2017a, 2017b, 2018; Hora and Miley, 2018; Eliezer *et al.*, 2016).

Computations based on cases as in Figure 1 but with picsecond high-intensity block ignition were studied since 2000 for explanations of the results of Sauerbrey (1996) by related experiments and computations to analyse this ignition mechanism (Hora *et al.*, 2002a, 2002b, 2002c; Laska *et al.*, 2003; Badziak *et al.*, 2003; Wolowski *et al.*, 2003; Osman *et al.*, 2004; Hora, 2004) the results of which were derived by further international support including the IAEA (UN-International Atomic Energy Agency in Vienna) (Cang *et al.*, 2005; Hora *et al.*, 2007, 2008). The high-energy density non-thermal equilibrium (low-temperature) fusion ignition by plasma blocks from picosecond ultrahigh acceleration were studied also based on the measurements by Sauerbrey (1996) but also at other centers in Poland, Hungary, Shanghai, and few other "fast ignition" projects. When from 2008 (Hora *et al.*, 2008) instead of the most studied DT fusion, the usually five orders of magnitudes lower gaining HB11 (usually at classical thermal equilibrium) were used with non-thermal equilibrium for block ignition, it was most surprising that then gains like those of DT were the result (Hora *et al.*, 2010). This increase by five orders of magnitudes for HB11 was – similar to the measurements of Norreys *et al.* (1998) – due to the non-equilibrium conditions of the block ignition. This was then in advance resulting in the conclusions of Hora *et al.* (2015, 2017a) that could be concluded from the pioneering measurements of laser-produced HB11 fusion (Belyaev *et al.*, 2005; Labaune *et al.*, 2013). The needed non-thermal and non-linear force-dominating conditions

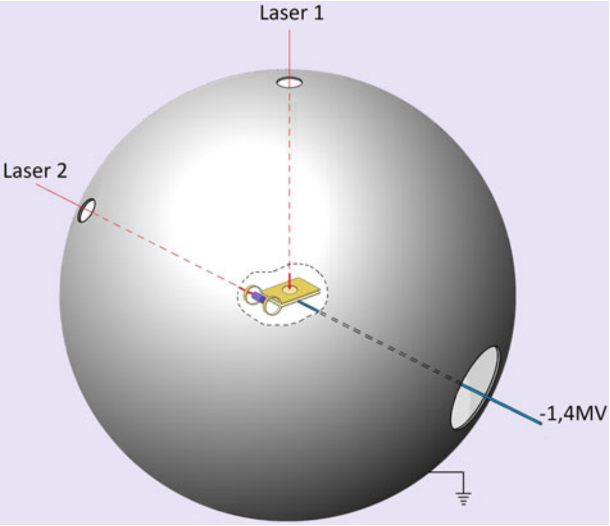

Fig. 4. Clean generator for electric power by laser boron fusion with nanosecond laser 1 to produce the kilotesla magnetic field in the capacitor–coil (Fujioka *et al.* 2013) reaction unit in the center of the spherical generator (Hora *et al.*, 2015, 2017a) and the >10 PW-ps laser pulse 2 to initiate end-on the non-thermal non-linear force-driven reaction in the HB11 fuel cylinder.

for HB11 fusion had been postulated earlier (Hora, 1988) at a conference in Princeton in 1987 for justifying alternative research on aneutronic fusion in contrast to LTE conditions.

Design of laser boron fusion reactor

Though details of the clean and low-cost laser boron fusion reactor have been discussed before (Hora *et al.*, 2017a, 2017b, 2017c), the following points should be underlined. The reaction unit in the center of the reaction sphere (Fig. 4) with the cylindrical solid density fuel of hydrogen and boron ^{11}B is ignited by the direct-drive pulses of the picosecond laser 2 of more than 10 PW power. There is a flexibility about the details of the pulse profile that on the one hand is a problem how to generate this (Danson *et al.*, 2018), but on the other hand, it permits modifications for producing optimized conditions. The same optimization is possible by the time dependence of the kilotesla magnetic field in the capacitor coil depending on the quality of the nanosecond laser pulse 1 of at least kJ energy. The laser technology permits a wide range of variations.

Another flexibility in modifications is the preparation of the fuel density within the first 10 µm at the target for the direct-drive interaction area of laser 2 at the end area of the fuel. This influences the initiation of the picosecond ignition process for the propagating reaction plane through the fuel as it was the result of a very large number of cases for calculation with the genuine multi-fluid computations (Lalousis and Hora, 1983; Hora *et al.*, 1984, 2015). These details are also of importance when the nonlinear force acceleration process in target layers is used for the generation of space charge neutral ion beams, with more than million times higher ion densities than the best classical accelerator can produce (Hora *et al.*, 2017a, 2007) for ion energies of few hundred MeV energy cancer treatment or for space craft propulsion (Hora *et al.*, 2011; Hora and Miley 2018; Lalousis *et al.*, 2013; Hoffmann *et al.*, 2018). Even nearly monoenergetic proton beams above GeV (Xu *et al.*, 2016; 2018) are related to the results of Hora *et al.* (2018).

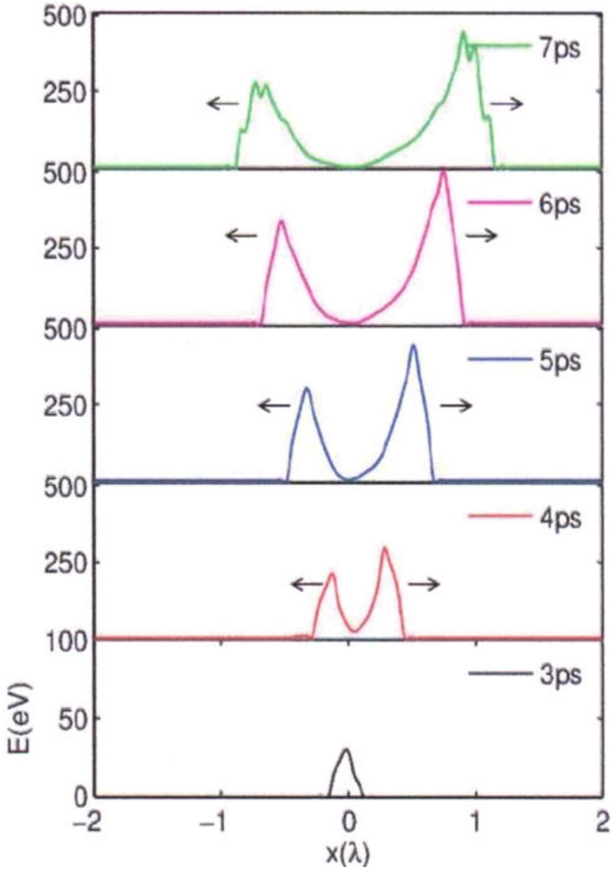

Fig. 5. PIC computation of the dielectric explosion of the plasma blocks at plasma densities close to the critical density (Hora *et al.*, 2018) confirming of the result of hydrodynamic computations (Fig. 1) as necessary process for the very rare measurement of the blue Doppler shift in the reflected light (Sauerbrey, 1996; Zhang *et al.*, 1998; Hora, 1969, 1981).

It is shown in the 2nd and 3rd Sections that the ultrahigh plasma-block acceleration is the essential mechanism for the non-LTE process of the low-temperature ignition (Hora *et al.*, 2015, 2017a, 2017b, 2017c, 2018) of the laser boron fusion for the new reactor design. This was possible only by the extreme contrast ratio (Danson *et al.*, 2018) of the laser pulses as it was realized in retrospect only (Hora, 2016) by the blue Doppler shift of spectral lines (Sauerbrey, 1996; Zhang *et al.*, 1998; Földes *et al.*, 2000). The PIC computation with inclusion of dielectric response was difficult and succeeded only recently (Xu *et al.*, 2016, 2018; Hora *et al.*, 2018) to confirm the earlier hydrodynamic derivation of basic requirements for the operation of the reactor design of Figure 5.

A further problem had to be solved with respect to the secondary neutron production of HB11 fusion. The primary HB11 reaction [Eq. (5)] is indeed free from neutron generation, but it is well known that secondary reactions produce about a neutron per thousand generated α particles of helium. The elimination of these neutrons is possible by screening the reactor sphere of Figure 4 by an equipment of about 10 cm thickness to the level that the reactor works clearly below the level of any radioactive pollution problem (Eliezer *et al.*, 2017). This neutron capturing, for example, for a reactor for 100 PW generation of electricity does not need a replacement of the screening material for a few years. The advantage compared with the radioactive waste problem of fission reactors is that the neutrons decay with a half-life of 14.69 min into harmless electrons and protons.

Patenting procedures (Hora, 2014) are based on HB11 reactions with some similarity to (Margarone *et al*., 2013) based on non-linear force ultrahigh acceleration processes. The essential difference consists in the fact that the patent (Hora, 2014) is a combination with the otherwise earlier known kilotesla magnetic field generated by capacitor coils (Fujioka *et al*., 2013) for the cylindrical trapping of the reaction that is necessary for the reactor of Figure 4 to provide non-LTE low-temperature laser fusion.

Acknowledgements. This text is from a plenary lecture at the Third Symposium on High Power Laser Research and Engineering, 9–13 April 2018 in Suzhou/China. These results are based on the contribution by co-authors in the related references with acknowledging great thanks.

References

Badziak J, Kozlov AA, Makowski J, Paris P, Ryz L, Wolowski J, Woryna E and Vankov AB (1999) Investigations of ion streams emitted from plasma produced with a high power picosecond laser. *Laser and Particle Beams* **17**, 323–329.

Badziak J, Hora H, Woryna E, Jablonski S, Laska L, Parys P, Rohlena K, and Wolowski J (2003) Experimental evidence of differences in properties of fast ion fluxes form short-pulse and long-pulse laser-plasma interaction. *Physics Letters* **A315**, 452.

Belyaev VS, Matafonov AP, Vinogradov VI, Krainov VP, Lisista VS, Roussetski AS, Ignatyev GN and Adrianov VP (2005) Observation of neutron-less fusion reactions in picosecond laser plasmas. *The Physical Review* **E72**, 026406

Bigot B (2017) "Overall status of the ITER project" in Proceedings of the IEEE SOFE Symposium, Shanghai/China June 2017, pp. 4–8.

Bobin J-L (1974) Nuclear fusion reactions in fronts propagating in solid DT. In Schwarz H and Hora H (eds), *Laser Interaction and Related Plasma Phenomena*. New York: Plenum Press, Vol. **4B**, 465–494.

Cang Y, Osman F, Hora H, Zhang J, Badziak J, Wolowski J, Jungwirth K, Rohlena K and Ullschmied J (2005) Computations for nonlinear force driven plasma blocks by picosecond laser pulses for fusion. *Journal of Plasma Physics* **71**, 35–51.

Chu MS (1972) Thermonuclear reactions waves at high densities. *Physics of Fluids* **15**, 412.

Danson C, Egan D, Elsmere S, Girling M, Arvey E, Hillier D, Hoarty D, Masoero D, Hussei S, McLoughlin J, Parker S, Penman R, Sawyer D, Treadwell P, Winter D and Hoppe N (2018) 400 TW operation of orion at ultrahigh contrast, 3rd HPLSE Symposium Suzhou, Abstracts p.62.

Eliezer S, Hora H, Korn G and Nissim N and Martinez-Val JM (2016) Avalanche proton-boron fusion based on elastic nuclear collisions. *Physics of Plasmas* **23**, 050704.

Eliezer S, Hora H and Nissim N (2017) German Patent application 10 2017 010927.3, Clean laser boron fusion without secondary nuclear waste, 29 Nov. 2017.

Földes I, Bakos JS, Gal K, Juhasz Y, Kedves MA, Koscis G, Syatmari S and Verex G (2000) Properties of high harmonics generation by UV laser pulses on solid surfaces. *Laser Physics* **10**, 264–269.

Fujioka S, Zhang Z, Ishihara K, Shigemori K, HironakaI Y, Johazaki T, Sunahara A, Yamamoto N, Nakashima H, Watanabe T, Shiraga H, Nishimura H and Azechi H (2013) Kilotesla magnetic field due to a capacitor-coil target driven by high power laser. *Nature Scientific Reports* **3**, 1170–1176.

Grieger G and Wendelstein Team (1981) Plasma Physics and Controlled Fusion Research (1980), Proceedings Vl. 1 pp. 173 and 185, see also Chapter 2.6 of Hora (1991).

Hoffmann DDH, Zhao YT and Katrick P (2018) Non-ideal plasma at elastic nuclear collisions for avalanche boron fusion. 3rd HPLSE Symposium Suzhou, Abstracts p.46.

Hora H (1969) Nonlinear Effects and Non-thermal Plasmas. *Physics of Fluids* **12**, 182.

Hora H (1981) *Physics of Laser Driven Plasmas*. New York: Wiley.

Hora H (1988) Nuclear effects and non thermal plasmas. *Nuclear Instruments and Methods* **A271**, 117.

Hora H (1991) *Plasmas at High Temperature and Density*. Heidelberg: Springer.

Hora H (2004) Developments in inertial fusion energy and beam fusion at magnetic confinement. *Laser and Particle Beams* **22**, 439.

Hora H (2009) Laser fusion with nonlinear force driven plasma blocks: thresholds and dielectric effects. *Laser and Particle Beams* **27**, 207.

Hora H (2014) Method for generating electrical energy by laser fusion and fusion reactor. Patent PCT/EP2014/003281 world patent WO 2-15/144190 A1 with granting Chinese Patent No. 2905560; Patent No.: ZL 201480077324.3 and US Application 20170125129A1, May 2, 2017. Priority 23.03.2014.

Hora H (2016) *Laser Plasma Physics*, 2nd Edn. Bellingam WA: SPIE Books.

Hora H, Lalousis P and Eliezer S (1984) Analysis of the Inverted Double Layers in Nonlinear Force Produced Cavitons at Laser-Plasma Interaction. *Physical Review Letters* **63**, 1650.

Hora H and Miley GH (2018) Laser driven plasma blocks for space propulsion. German Patent application 10 2018 001 430.5, Opto-mechanical driven HB11 Space Propulsion 14 Feb 2018.

Hora H, Badziak J, Boody FP, Höpfl R, Jungwirth K, Kralikowa B, Kraska J, Laska L, Parys P, Perina V, Pfeifer M, Rohlena K, Skala J, Ullschmied J, Wolowski J and Woryna E (2002a) Effects of ps and ns laser pulses for giant ion source. *Optics Communications* **207**, 333.

Hora H, Peng H, Zhang W and Osman F (2002b) New skin depth interaction by ps-TW laser pulses and consequences for fusion energy. *SPIE Proceedings* **4914**, 37.

Hora H, Badziak J, Boody FP, Höpfl R, Jungwirth K, Kralikova B, Kraska J, Laska L, Pfeifer M, Rohlena K, Skala J, Ullschmied J, Wolowski J and Woryna W (2002c) Skin Depth Theory for Nonlinear-Force Driven Block Ignition Laser-ICF Based on Anomalous Picosecond Terawatt Laser Plasma Interaction, Eurpean Conference on Laser Interaction with Matter ECLIM, Mosocw, O.N. Krokhin et al eds., *SPIE Conference Proceedings No. 5228*, p. 295

Hora H, Badziak J, Read MN, Li YT, Liang TJ, Liu H, Shang ZM, Zhang J, Osman F, Miley GH, Zhang WY, He XT, Peng HS, Glowacz S, Jablonski S, Wolowski J, Skladanowski Z, Jungwirth K, Rohlena K and Ullschmied J (2007) Fast ignition by laser driven beams of very high intensity. *Physics of Plasmas* **14**, 072701.

Hora H, Malekynia B, Ghoranneviss M, Miley GH and He X (2008) Twenty times lower ignition thresholds for laser driven fusion using collective effects and the inhibition factor. *Applied Physics Letters* **93**, 011101.

Hora H, Miley GH, Ghorannviss M, Malekynia H, Azizi N and He X-T (2010) Fusion energy without radioactivity: laser ignition of solid hydrogen-boron(11) fuel. *Energy and Environmental Science* **3**, 479.

Hora H, Miley GH, Yang X and Lalousis P (2011) Strong shock-phenomena at petawatt-picosecond lasers. *Astrophysics and Space Science* **336**, 225–228.

Hora H, Korn G, Giuffrida L, Margarone D, Picciotto A, Krasa J, Jungwirth K, Ullschmied J, Lalousis P, Eliezer S, Miley GH, Moustaizis S and Mourou G (2015) Fusion energy using avalanche increased boron reactions for block ignition by ultrahigh power picosecond laser pulses. *Laser and Particle Beams* **33**, 607.

Hora H, Eliezer S, Kirchhoff GJ, Nissim N, Wang JX, Lalousis P, Xu YX, Miley GH, Martinez-Val JM, McKenzie W and Kirchhoff J (2017a) Road Map to Clean Energy Using Laser Beam Ignition of Boron-Hydrogen Fusion. *Laser and Particle Beams* **35**, 730.

Hora H, Eliezer S, Nissim N and Lalousis P (2017b) Non-thermal laser driven plasma-blocks for proton boron avalanche fusion as direct drive option. *Matter and Radiation at Extremes (Elsevier)* **2**, 177–189.

Hora HG, Korn Eliezer S, Nissim N, Lalousis P, Giuffrida L, Margarone D, Picciotto A, Miley GH, Moustaizis S, Martinez-Val J-M, Barty CPJ and Kirchhoff GJ (2017c) Avalanche Boron Fusion by Laser Picosecond Block Ignition with Magnetic Trapping for Clean and Economic Reactor. *High Power Laser Science and Engineering* **4**, e35.

Hora H, Eliezer S, Wang JX, Korn G, Nissim N, Xu YX, Lalousis P, Kirchhoff KJ and Miley GH (2018) Laser Boron Fusion Reactor with

Picosecond Petawatt Block Ignition. *IEEE Transactions on Plasma Science* **46**, 1191.

Hurricane OA, Callahan DA, Casey DT, Celliers PM, Cerjan C, Dewald EL, Dittrich TR, Döppner T, Hinkel DE, Berzak LF, Hopkins LFB, Kline JL, Le Pape S, Ma T, MacPhee AG, Milovich JL, Pak A, Park H-S, Patel PK, Remington BA, Salomonson JD, Springer PT and Tommasini R (2014) Fuel gain exceeding unity in an inertial confined fusion implosion. *Nature* **506**, 343.

Krasa J, Klir D, Velyhan A, Margarone D, Krousky E, Jungwirth K, Skala J, Pfeiffer M, Kravarik J, Kubes P, Rezac K and Ullschmied J (2013) Observation of repetitive bursts in emission of fast ions and neutrons in sub-nanoseconds laser-solid experiments. *Laser and Particle Beams* **31**, 395.

Labaune C, Deprierraux S, Goyon S, Loisel C, Yahia G and Rafelski J (2013) Fusion reactions initiated by laser accelerated particle beams in laser produced plasmas. *Nature Communications* **4**, 2506.

Lalousis P and Hora H (1983) First direct electron and ion fluid computation of high electrostatic fields in dense inhomogeneous plasmas with subsequent nonlinear laser interaction. *Laser and Particle Beams* **1**, 283–304.

Lalousis P, Hora H, Eliezer S, Martinez-Val JM, Moustaizis S, Miley GH and Mourou G (2013) Shock mechanisms by ultrahigh laser accelerated plasma blocks in solid density targets for fusion. *Physics Letters A* **377**, 885–888.

Laska L, Jungwirth K, Kralikova B, Kraska J, Pfeifer M, Rohlena K, Skala J, Ullschmied J, Basziak J, Parys P, Wolowski J, Woryna E, Gammino S, Torrisi L, Boody FB and Hora H (2003) Generation of multiply charged ions at low and high laser-power densities. *Plasma Physics and Controlled fusion* **45**, 585–599.

Margarone D, Korn G, Picciotto A and Bellutti P (2013) Laser fusion system and method. European Patent application EP 2833365 A2, Priority 13.07.2013.

Margarone D, Picciotto A, Velyhan A, Krasa J, Kucharik M, Mangione A, Szydlowsky A, Malinowska A, Bertuccio G, Shi Y, Crivellari M, Ullschmied J, Bellutti P and Korn G (2015) Advanced scheme for high-yield laser driven nuclear reactions. *Plasma Physics and Controlled Fusion* **57**, 014030.

Norreys PA, Fews AP, Beg FN, Bell AR, Dangor DA, Lee P, Neslon MB, Schmidt H, Tatarakis M and Cable MD (1998) Neutron production from picosecond laser irradiation of deuterated targets at intensities of 10^{19} W/cm^2. *Plasma Physics and Controlled Fusion* **40**, 175.

Osman F, Cang Y, Hora H, Cao L, Liu H, He X, Badziak J, Parys AB, Wolowski J, Woryna E, Jungwirth K, Kralikova B, Kraska J, Laska L, Pfeifer M, Rohlena K, Skala J, Ullschmied J (2004) Skin depth plasma front interaction mechanisms with prepulse suppression to avoid relativistic self-focusing for high-gain laser fusion. *Laser and Particle Beams* **22**, 83.

Picciotto A, Margarone D, Velyhan A, Bellini P, Krasa J, Szydlowski A, Bertuccio G, Shi Y, Margarone A, Prokupek J, Malinowska A, Krouski E, Ullschmied J, Laska L, Kucharik M and Korn G (2014) Boron-proton nuclear-fusion enhancement induced in boron-doped silicon targets by low contrast pulsed laser. *The Physical Review* **X**, 4.

Sauerbrey R (1996) Acceleration of femtosecond laser produced plasmas. *Physics of Plasmas* **3**, 4712.

Strickland D and Mourou G (1985) Compression of amplified chirped optical pulses. *Optics Communications* **65**, 219.

Wolowski J, Badziak J, Boody FB, Hora H, Hnatowicz V, Jungwirth K, Kraska J, Laska L, Parys P, Perina V, Pfeifer M, Rohlena K, Ryc L, Ullschmied J and Woryna E (2003) Fast ion emission from the plasma produced by the PALS laser system. *Plasma Physics and Controlled Fusion* **44**, 1277.

Xu YX, Wang JX, Qi M, Li Y, Xing Y and Long L (2016) Improving the quality of proton beams via double targets driven by an intense circularly polarized laser pulse. *AIP Advances* **6**, 105304.

Xu YX, Wang JX, Hora H, Yifan XQ, Yang XK and Zhu WJ (2018) Plasma Block acceleration based upon the interaction between double targets and an ultra-intense linearly polarized laser pulse. *Physics of Plasmas* **25**, b 043102.

Zhang J (2018) Plenary Announcement about the Initiative of Chinese Academy of Science for Fusion with ps Laser Pulses of Extreme Power, 12 April 2018 at 3rd HPLSE Symposium Suzhou/China

Zhang M, He JT, Chen DB, Li ZH, Zhang Y, Wang L, Feng BL, Zhang DF, Tang XW and Zhang J (1998) Effects of a prepulse on γ-ray radiation produced by a femtosecond laser with only 5-mJ energy. *Physical Review E* **57**, 3745.

Zhou J (2018) Opening presentation of Mini-Workshop at 3rd High Power Laser Science and Engineering Symposium at Suzhou/China on 12 April.