Laser and Particle Beams (2009), *27*, 491–496. Printed in the USA.

doi:10.1017/S026303460999022X

Nonlinear force driven plasma blocks igniting solid density hydrogen boron: Laser fusion energy without radioactivity

H. HORA,[1] G.H. MILEY,[2] N. AZIZI,[3] B. MALEKYNIA,[3] M. GHORANNEVISS,[3] AND X.T. HE[4]

[1]Department of Theoretical Physics, University of New South Wales, Sydney, Australia
[2]Department of Nuclear, Plasma and Radiation Engineering, University of Illinois, Urbana, Illinois
[3]Plasma Physics Research Centre, Islamic Azad University, Tehran-Poonak, Iran
[4]Institute of Applied Physics and Computational Mathematics, Bejing, China

(Received 5 April 2009; Accepted 12 June 2009)

Abstract

Energy production by laser driven fusion energy is highly matured by spherical compression and ignition of deuterium-tritium (DT) fuel. An alternative scheme is the fast ignition where petawatt (PW)-picosecond (ps) laser pulses are used. A significant anomaly was measured and theoretically analyzed with very clean PW-ps laser pulses for avoiding relativistic self focusing. This permits a come-back of the side-on ignition scheme of uncompressed solid DT, which is in essential contrast to the spherical compression scheme. The conditions of side-on ignition thresholds needed exorbitantly high energy flux densities E^*. These conditions are now in reach by using PW-ps laser pulses to verify side-on ignition for DT. Generalizing this to side-on igniting solid state density proton-Boron-11 (HB11) arrives at the surprising result that this is one order of magnitude more difficult than the DT fusion. This is in contrast to the well known impossibility of igniting HB11 by spherical laser compression and may offer fusion energy production with exclusion of neutron generation and nuclear radiation effects with a minimum of heat pollution in power stations and application for long mission space propulsion.

Keywords: Block ignition; Fast ignition; Fusion without neutrons; Hydrogen-Boron fusion; Laser driven fusion energy; Patawatt lasers; Side-on ignition; Skin layer acceleration

1. INTRODUCTION

Very clean energy can be produced from the fusion reaction of protons with ^{11}B (hydrogen-boron reaction HB11), because no neutrons are produced, and the resulting alpha particles are mono-energetic of 2.9 MeV, which is ideal for high-efficient direct conversion into electricity (Miley, 1976). Secondary reactions lead to radioactivity, but this is less per produced energy than burning coal due to its natural contents of 2 ppm uranium (Weaver *et al.*, 1973), and may be considered as negligible. However, it was from the beginning evident that this fusion reaction is much more difficult than using deuterium-tritium (DT) fusion fuel, as seen from the spherical laser compression of HB11, which need densities of 100,000 times the solid state (Hora, 1975, 2007). Nevertheless, a basically new approach to laser fusion seems to be possible by the more recent achievement of laser pulses in the petawatt-picosecond (PW-ps) range thanks to the discovery of chirped pulse amplification (Strickland & Mourou, 1985; Perry & Mourou, 1994; Mourou &Tajima, 2002) or the Szatmari-Schäfer (Szatmari & Schäfer, 1988; Földes & Szatmari, 2008) method.

The PW-ps laser pulses were developed for the fast ignition method (Tabak *et al.*, 1994) in laser fusion but it also can be used for a basic alternative of laser fusion where a side-on ignition of solid density fuel is used (Chu, 1972) in contrast to the spherical laser compression. In the following, it is essential that an updating (Ghoranneviss *et al.*, 2008; Hora *et al.*, 2008; Malekynia *et al.*, 2009) is reached for the side-on ignition of solid state fusion fuel initiated by Chu (1972) and Bobin (1974) to be combined with recently discovered block ignition (Hora *et al.*, 2002, 2007; Hora, 2003, 2009; Yazdani *et al.*, 2009) using nonlinear (ponderomotive) force acceleration by PW-ps laser pulses producing highly directed space charge quasi-neutral ion current densities exceeding 10^{11}Amps/cm^2 by suppression of relativistic self-focusing. The same fully plane geometry acceleration if ions were generated in a similar way (Nuckolls & Wood, 2002).

Address correspondence and reprint requests to: H. Hora, Department of Theoretical Physics, University of New South Wales, Sydney 2052, Australia. E-mail: h.hora@unsw.edu.au

Similarity is given with the side-on ignition of DT fusion with densities not very much above the solid state using very intense electron beams driven by PW-ps laser pulses (Hora, 2003) instead of using the here considered ion beams. The side-on ignition was considered for HB11 from the beginning (Hora, 2002) and a clarification was reached recently by the surprising result that this is possible with about one order of magnitude more difficult conditions than for DT. This was reached by extending the updated conditions of side-on ignition for DT (Hora *et al.*, 2008) to the case of HB11 (Azizi *et al.*, 2009).

The very negative results of HB11 laser fusion by spherical compression at an early stage with the need of an exorbitant compression in the range of 100,000 times of the solid state (Hora, 1975), was confirmed later by very detailed computations of volume ignition (Scheffel *et al.*, 1997). Even at higher densities, a retrograde dependence showed a limit at 200,000 times the solid state. The optimum ignition temperature dropped from more than 130 keV (without re-absorption) to 23 keV due to reheat and partial self-absorption of radiation, but the necessary laser pulse energies were exorbitant with several dozens of MJ to produce total gains per input laser energy of about 20. Other arguments about the impossibility of laser driven HB11 fusion by spherical laser compression were discussed on the basis of the equation of state (Eliezer *et al.*, 2007). The situation is very different for DT fusion with spherical laser irradiation and very high compression (Moses *et al.*, 2006; Moses, 2008) where the many year developments are leading next to a physics solution for laser fusion. The next task for developing the economic power station is then to reduce the costs for the driving lasers by very many orders of magnitude, which is possible in principle similar to the cost reduction of transistors.

The HB11 fusion is the first kind of clean energy production without any one of the environmental disadvantages of nuclear energy. This may be important for consideration and decisions in the future in a similar way as a drastic cost reduction of solar cells may be possible by producing the p-n junctions with sub-threshold electron beam irradiation (Ghoranneviss *et al.*, 2006; Hora, 2007) or as energy production from other sources under development. The importance of the HB11 fusion for space propulsion was elaborated (Miley *et al.*, 2008).

2. BLOCK IGNITION FOR DEUTERIUM-TRITIUM

Side-on ignition for fusion using plasma blocks driven by nonlinear forces of laser interaction is based on preventing self-focusing of the laser beam such that it remains uniformly distributed over a broad interaction area of the target surface. Physically, this requires strong suppression of laser pre-pulses, i.e., a very high contrast ratio (ratio of the main pulse intensity to pre-pulse intensity). This has to be higher than 10^8 for times less than a dozens of ps before arrival of the main pulse. The resulting plasma blocks have high momentum and are directed back toward the incoming laser beam. Momentum conservation causes an imploding block of plasma toward the inner portion of the target fuel and is considered to produce a thermonuclear reaction wave as elaborated by Chu (1972).

The necessary high velocity quasi-neutral plasma blocks are generated by skin-layer acceleration by nonlinear forces (Hora *et al.*, 2007). This effect was first observed experimentally, although long expected theoretically, and predicted from numerical studies before (Hora, 1991, Section 10.5). Only after the very clean ultra-intense TW-ps laser pulses were available (Sauerbrey, 1996; Zhang *et al.*, 1998; Badziak *et al.*, 1999), the predicted block generation could be measured where relativistic self-focusing was excluded, permitting the plane interaction front for nonlinear force acceleration (Hora, 2003; Hora *et al.*, 2007). Since this acceleration of the ions is electro-dynamic by the nonlinear force, and not thermo-kinetic, the observed blocks (pistons) are highly directed, and have a comparably low temperature. The measured DT ion beam current density j in the space charge neutral block

$$j > j^* = 10^{11}\ \text{A/cm}^2, \tag{1}$$

exceeds the threshold value j^* for a fusion reaction wave in solid DT fusion fuel.

Another necessary condition for the side-on ignition was that the energy flux density E^* of the irradiation had to be larger than the threshold E_0^* for DT

$$E^* > E_0^* = 4.5 \times 10^8\ \text{J/cm}^2. \tag{2}$$

As shown from the hydrodynamic analysis by Chu (1972). This can be seen in Figure 1 showing Chu's results of the generated maximum temperature T in irradiated solid DT on time t with the energy flux density E^* as parameter, which values were reproduced numerically (Ghoranneviss

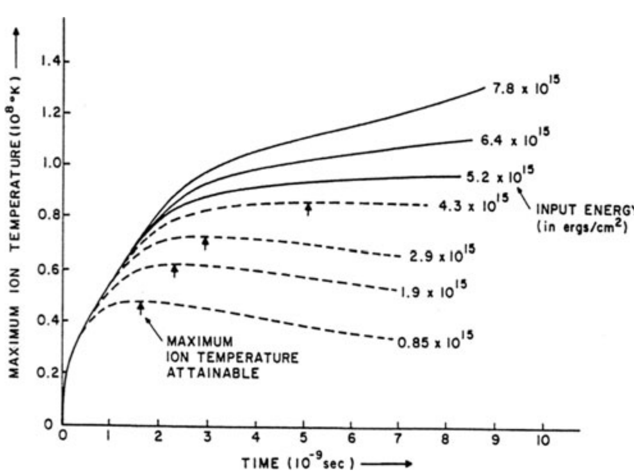

Fig. 1. Characteristics of the maximum temperature T on time t for parameters E^* of energy flux density in ergs/cm^2 for side-on fusion ignition of solid state DT from Figure 2 of Chu (1972).

https://doi.org/10.1017/S026303460999022X Published online by Cambridge University Press

et al., 2008). As soon as T is merging into a constant time dependence, the threshold E_{th}* is reached. The results with the threshold temperature for ignition T_{ign} are

$$E^*_{th} = 4.5 \times 10^8\,\mathrm{J/cm^2} \quad \text{at } T_{ign} = 7.2\,\mathrm{keV} \quad (\mathrm{DT}). \qquad (3)$$

An updating of Chu's calculations with inclusion of the reduction of thermal conduction between hot and cold plasmas given by an inhibition factor F* due to the electric double layer, and with inclusion of the collective effect for the stopping length of the alpha particles in the plasma resulted in a decrease of E_{th}* by a factor 20 (Hora *et al.*, 2008; Malekynia *et al.*, 2009; Hora, 2009). Though this value is still very high, this is not too far from the experimental conditions achieved in the experiments (Hora *et al.*, 2007) or for next generation PW-ps laser pulses.

It should be mentioned that the explanation of the very first observation of plane plasma front acceleration based with very clean TW-ps laser pulses by Sauerbrey (1996)—to be understood from nonlinear force interaction (Hora, 2003; Hora *et al.*, 2007)—was the merit of Peter Hammerling (see Hora *et al.*, 2004). This generation of the highly directed plasma or ion blocks accelerated perpendicularly to the target surface by nonlinear forces (Hora, 1974), is essential for the proton fast ignition scheme (Roth *et al.*, 2005). The extraordinary importance of the suppression of the pre-pulses for generating very clean laser-plasma interaction—after realizing its importance to avoid relativistic self-focusing (Hora *et al.*, 2002; Hora, 2003)—was recognized also in proton acceleration measurements (Kaluza *et al.*, 2004, Neely *et al.*, 2006). The theoretical understanding of the nonlinear force action on the electron cloud and the subsequent highly directed ion acceleration by the electric fields as a double layer mechanism (Hora *et al.*, 1984) was a result of hydrodynamics and was appearing also in the particle-in-cell treatments, which method was discovered by Wilks *et al.* (1992). The application of these accelerations and electric field mechanisms to experimental results can be seen in Table 1 of Badziak *et al.* (2005). A significant measurement is the decrease of the proton energy on the backside of targets (Neely *et al.*, 2006) where the thickness varies from 0.1 to 10 μm. This is supported by comparable hydrodynamic evaluation of the collisionless absorption of fs laser pulses of near-relativistic intensities by the nonlinear force (Batchelor & Stening, 1985). These evaluations of the nonlinear force were based on the rare discovery to solve a nonlinear differential equation exactly with elementary methods.

3. CHU-THRESHOLD FOR HYDROGEN BORON

To be consistent with the results of Chu (1972) with DT fuel, computations were first performed based on his assumptions for HB11 fusion. Using the HB11 fusion cross-sections, the hydrodynamic calculation resulted in the time dependence of the plasma temperature shown here in Figure 2 in analogy to the Figure 1 for DT. The parameter of the curves is the energy flux density E*. The aim is to find the value of E_{th}* of the ignition threshold where the plasma temperature T merges into a constant value in the dependence on time t. The evaluation of the threshold conditions needs a very detailed and high precision numerical following up of the detailed curves of Figure 2 to exclude the very slight decay on time t. This value is found to be for HB11 with the ignition temperature T_{ign} given by the curve in Figure 2 with the parameters

$$E^*_{th} = 1 \times 10^9\,\mathrm{J/cm^2} \quad \text{at } T_{ign} = 87\,\mathrm{keV} \quad (\mathrm{HB11}). \qquad (4)$$

These results are remarkably modest compared with the values of DT of Eq. (3) according to Chu (1972), Figure 1. In view of the exorbitant difference between DT and HB11 for volume ignition based on spherical pellet compression, it is really surprising how much easier the ignition of HB11 works for a side-on generated thermonuclear reaction front.

After Figure 2 showed the result of HB11 for strictly using the presumptions used by Chu (1972) for DT, it was interesting to see how the inclusion of the inhibition factor and of the collective stopping power—similar to the DT case (Hora *et al.*, 2008)—will improve the conditions for HB11. Figure 3 shows the result selected for the threshold conditions. In this case the values of Eqs (4) (derived for the Chu conditions) are reduced to

$$E^*_{th} = 4.5 \times 10^8\,\mathrm{J/cm^2} \quad \text{at } T_{ign} = 85\,\mathrm{keV} \quad (\mathrm{HB11}). \qquad (4a)$$

It is evident that the reduction for HB11 is less pronounced than for DT (Hora *et al.*, 2008). The reason is obviously the very much higher reaction temperature for HB11 where then the thermal conduction effects of the plasma and the stopping

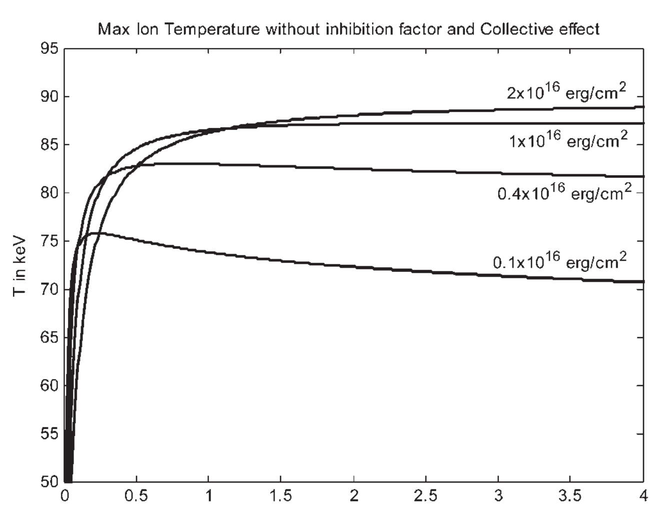

Fig. 2. In analogy to Figure 1 for side-on ignition of solid state DT with his same detailed hydrodynamic presumptions, the plasma temperature T for hydrogen-boron(11) as function of the time t is given for a parameter E* in erg/cm^2.

https://doi.org/10.1017/S026303460999022X Published online by Cambridge University Press

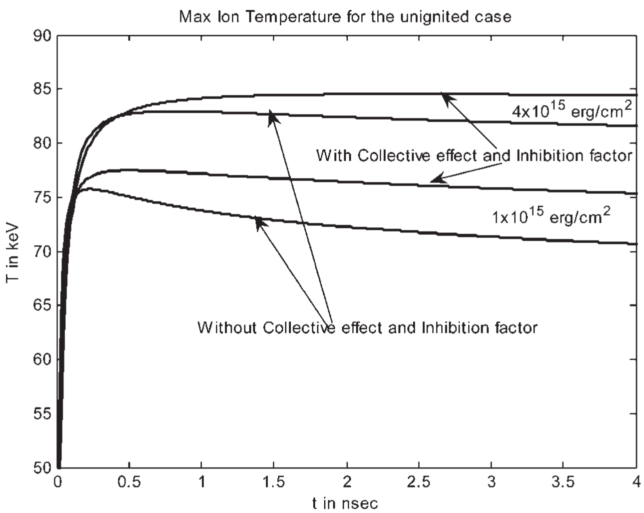

Fig. 3. Characteristics for the side-on conditions following the laser ignition of solid state density HB11 compared with Figure 2 are given with inclusion of the inhibition factor and with the collective stopping power similar to the former calculated reduction for DT (Hora *et al.*, 2008).

mechanisms of the alpha particles is comparably less pronounced.

The correctness of the shown hydrodynamic results may be seen in the derived proof of consistency in the resulting temperatures. In the case of DT, the ignition without reheat and without partial X-ray re-absorption dropped from the (energy averaged value of) 11.5 keV for spherical compression to 5.8 keV even only under the simplified conditions of Chu (1972). There is a clear similarity to the case of HB11. In this case, the temperature for the spherical compression without reheat and without partial self-absorption is in the range above 130 keV (Scheffel *et al.*, 1997), while the here reported ignition of solid fusion fuel arrived at 85 keV temperature for the side-on ignition even only with the assumptions of Chu (1972), Figures 2 and 3, and Eq. (4a).

One point of special attention is the temperature T as being the non-equilibrium electron temperature in the hydrodynamic analysis. For equilibrium between electron and ion temperature, T has to be above a threshold T^* because the shock wave process following Chu (1972) does not permit a modification due to re-absorption of bremsstrahlung as in the volume processes at spherical compression (Scheffel *et al.*, 1997). For DT without modification T^* is 4 keV. It was the result for all cases including inhibition and collective effects that the threshold for DT was always above 4.3 keV (Hora *et al.*, 2008). For HB11, the equilibrium temperature threshold is $T^* = 60$ keV. The results for side-on ignition of HB11 (Eqs. (4) and (4a)) were found to be higher with the presumptions used by Chu (1972) and respectively with inhibition and collective effects. Up to this point we can conclude with certainty that the side-on ignition for fusion energy production of HB11 is not more than about 10 times more difficult than of the DT reaction at solid state density for application of ps laser pulses above 10 PW power.

The generation of bremsstrahlung was included in all these calculations from the beginning with the work of Chu (1972). Details of the computations clarified (Hora *et al.*, 2008; Malekynia *et al.*, 2009) that these radiation losses were sufficiently low for DT and HB11 reactions. Otherwise no ignition at all could have been seen beginning with the plots of Chu (1972), Figure 1, and finally for the HB11 reactions in Figures 2 and 3. Bremsstrahlung is not nuclear radiation; its nature of X-radiation up to about 60 keV will not produce nuclear reactions for protons and boron nuclei. This permits sufficient screening in power stations known from the usual handling of X-rays and avoids any radioactivity in the material of the reactor.

4. EXTENSION OF THE CHU-COMPUTATIONS FOR SIDE-ON IGNITION OF DLI6 FUEL

It was of interest from the beginning to consider the generation of fusion energy by the reaction of D with the isotope 6 of lithium (DLi6). The reaction energy is 22.4 MeV, i.e., about two and a half times higher than from HB11 fusion and the reaction product are two alphas. This was mentioned by Miley (1976), especially underlining that no neutrons are produced primarily. Secondary reactions of the 11.2 MeV alphas may be more complex than the 2.9 MeV alphas of the HB11 reaction. The following evaluation is indeed very academic only because it ignores the very much stronger DD reaction at side-on ignition with generation of fusion energy as well as neutrons and radioactive nuclei. The interest however is more for application in medicine if the 11.2 MeV alphas are magnetically focused for cancer therapy and separated from the DD fusion reactions.

An updating of the numerical fitting of the highly accurately measured cross sections of DLi6 was of especial interest by Sir Ernest Titterton (Clark *et al.*, 1978) with similar views underlined by Sir Mark Oliphant (1989). At this time the only theoretical contributions about the cross sections were numerological adjustments of the experimental results while the fact of the fusion reaction e.g., of DT occurring at hundred times larger distance than the nuclear diameter could never be explained by Gamow factors or similar. A first physics theory using Schrödinger potentials with imaginary parts was arriving at the ever best fit of measurements of cross sections for DT later (Li *et al.*, 2004).

Using the cross sections (Clark *et al.*, 1978) for DLi6, the 22.4 MeV reaction energy and the other parameters for side-on ignition only with the conditions of Chu (1972), resulted in the characteristics of Figure 4. The characteristics show that the ignition threshold is

$$E^*_{\mathrm{th}} = 2.5 \times 10^9\ \mathrm{J/cm^2} \quad \text{at } T_{\mathrm{ign}} = 101\,\mathrm{keV} \quad \text{(DLi6)}. \tag{5}$$

It is to be underlined that the emission of the bremsstrahlung is included as done from the beginning by Chu (1972). The computations of Figure 4 are of some preliminary nature while the results of Figures 2 and 3 are based on

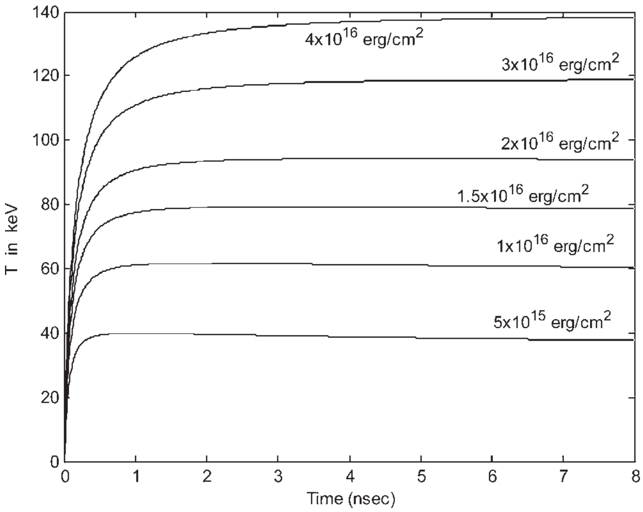

Fig. 4. Characteristics for the side-on ignition of uncompressed solid with the same conditions as Chu (1972) for the fusion energy generation from solid deuterium-lithium(6) fuel in analogy to DT (Fig. 1) and HB11 (Fig. 2).

computations using a critically revised code. What the results (5) can show at least is that the HB11 and the DLi6 reactions are basically not very much more difficult to be realized by side-on ignition than of solid DT in very strong contrast to the results for spherical laser compression for producing fusion energy.

5. CONCLUSIONS

A drastic difference between the well established spherical high-density compression scheme for laser fusion in contrast to the alternative scheme based on side-on ignition by laser driven high current density plasma blocks may simplify laser driven controlled fusion energy generation from solid density HB11 fuel in further future. The recently explored strong anomalies of nonlinear (ponderomotive) force driven plasma blocks (Hora *et al.*, 2007) are essential for the interaction of PW-ps laser pulses having a very high contrast ratio to avoid pre-pulses and subsequent relativistic self-focusing. This is the first fusion reaction for energy production which is environmentally clean and completely free from neutrons and from any disadvantages of nuclear radiation. It should not need to be underlined that the here presented new aspects of block ignition are in an early stage of exploration only, while the spherical ignition is in the highly matured state that the measurements (Moses *et al.*, 2006; Moses, 2008) expected during and after 2009 are to lead to the historical result of the first manmade controlled ignition of fusion when 1.9 MJ laser pulses produce 10^{19} DT fusion neutrons which is a gain of produced fusion energy per laser energy of 16.

ACKNOWLEDGEMENTS

It is gratefully acknowledged that the work at the Plasma Physics Research Center of the Islamic Azad University at Tehran-Poonak, Iran, was supported by the IAEA (Vienna) Coordinated Research Program No. 13508. The first author (H.H.) thanks Dr. G. Mank, Director of Physics at the IAEA, and Professor Milan Kalal of the Technological University Prague for an invitation as guest to the IAEA Coordinated Research Program No. 13011, and to the International Centre of Theoretical Physics, Trieste/Italy, for the contacts with IAEA and with Professor Reza Amrollahi, Akabir University Tehran, Iran for the contacts with Professor Rasoul Sadighi-Bonabi of the Sharif University in Tehran/Iran. Thanks are due to Professor Tara Desai for arranging a presentation of the main part of this work at the 4th Conference "Frontiers on Plasma Physics and Technology" in Kathmandu/Nepal, April 2009. Additions were in most appreciable way initiated from discussions with Academician Boris Yu. Sharkov, Director of the Institute for Theoretical and Experimental Physics, Moscow and Professor D. Neely from the Rutheroford Appleton Laboratory in the UK.

REFERENCES

Azizi, N., Hora, H., Miley, G.H., Malekynia, B., Ghoranneviss, M. & He, X.T. (2009). Threshold for laser driven block ignition for fusion energy from hydrogen-bron-11. *Laser Part. Beams* **27**, 201–205.

Badziak, J., Glowacz, S., Jablonski, S., Parys, P., Wolowski, J. & Hora, H. (2005). Laser-driven generation of high-current ion beams using skin-layer ponderomotive acceleration. *Laser Part. Beams* **23**, 401–410.

Badziak, J., Kozlov, A.A., Makowksi, J., Parys, P., Ryc, L., Wolowski, J., Woryna, E. & Vankov, A.B. (1999). Investigation of ion streams emitted from plasma produced with a high-power picosecond laser. *Laser Part. Beams* **17**, 323–329.

Batchelor, M.T. & Stening, R.J. (1985). Collisionless absroption of femtosecond laser pulses in plasmas by nonlinear forces. *Laser Part. Beams* **3**, 189–196.

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

Chu, M.S. (1972). Thermonuclear reaction waves at high densities. *Phys. Fluids* **15**, 412–422.

Clark, R.G., Hora, H., Ray, P.S. & Titterton, E. (1978). Evaluation of cross sections of the Li(d,α)α reaction. *Phys. Rev.* **C18**, 1127–1132.

Eliezer, S., Murakami, M. & Martinez-Val, J.-M. (2007). Equation of state and optimum compression in inertial fusion energy. *Laser Part. Beams* **25**, 585.

Földes, T.B. & Szatmari, S. (2008). On the use of KrF lasers for fast ignition. *Laser Part. Beams* **26**, 575.

Ghoranneviss, M., Sari, A.H., Hantehzadeh, M.H., Hora, H., Osman, F., Doolan, K.R., Höpfl, R. & Benstetter, G. (2006). Subthreshold defect generation by intense electron beams in semioconductors and microelectronics. *SPIE Proc.* **6035**, 377–383.

Ghoranneviss, M., Malekynia, B., Hora, H., Miley, G.H. & He, X. (2008). Inhibition factor reduces fast ignition threshold of laser fusion using nonlinear force driven block ignition. *Laser Part. Beams* **26**, 105–111.

Hora, H. (1974). Striated jets due to nonlinear ponderomotive forces in laser produced plasma at obliquely incident light. *Phys. Fluids* **17**, 939–947.

Hora, H. (1975). *Laser Plasmas and Nuclear Energy*. New York: Plenum Press.

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

Hora, H. (2002). Fusion reactor with petawatt laser. *German Patent Disclosure (Offenlegungsschrift)* DE 102 08 515 A1 (28 February 2002, declassified 5 SEP 2002).

Hora, H. (2003). Skin-depth theory explaining anomalous picosecond-terawatt laser plasma interaction II. *Czechosl. J. Phys*. **53**, 199–217.

Hora, H. (2007). *Klimakatastrophe Überwinden: Neuer Aufbruch zur Rettung der Umwelt (Overcome the Climatic Catastrophe: New Steps for Saving the Environment)*. Regensburg, Germany: S. Roderer Verlag.

Hora, H. (2009). Laser fusion with nonlinear force driven plasma blocks: Thresholds and dielectric effects. *Laser Part. Beams* **27**, 207–222.

Hora, H., Badziak, J., Read, M.N., Li, Y.-T., Liang, T.-J., Liu, H., Sheng, Z.-M., Zhang, J., Osman, F., Miley, G.H., Zhang, W., He, X., Peng, H., Glowacz, S., Jablonski, S., Wolowski, J., Skladanowski, Z., Jungwirth, K., Rohlena, K. & Ullschmied, J. (2007). Fast ignition by laser driven particle beams of very high intensity. *Phys. Plasmas* **14**, 072701-1/072701-7.

Hora, H., Badziak, J., Boody, F., Höpfl, R., Jungwirth, K., Kralikova, B., Krasa, J., Laska, L., Parys, P., Perina, P., Pfeifer, K. & Rohlena, J. (2002). Effects of picosecond and ns laser pulses for giant ion source. *Opt. Commun*. **207**, 333–338.

Hora, H., Lalousis, P. & Eliezer, S. (1984). Analysis of the inverted double layers in nonlinear force produced cavitons at laser-plasma interaction. *Phys. Rev. Lett*. **53**, 1650–1652.

Hora, H., Malekynia, B., Ghoranneviss, M., Miley, G.H. & He, X. (2008). Twenty times lower ignition threshold for laser driven fusion using collective effects and the inhibition factor. *Appl. Phys. Lett*. **93**, 011101/1–011101/3.

Hora, H., Osman, F., Cang, Y., Badziak, J., Jablosnki, S., Glowacz, S., Mileay, G.H., Hammerling, P., Wolowski, J., Jungwirteh, K., Rohlena, K., He, X., Peng, H. & Zhang, J. (2004). TW-ps laser driven blocks for light ion beam fusion in solid density DT, High-power Laser and Applications III. *SPIE Proc*. **5627**, 51–63.

Kaluza, M., Schreiber, J., Sandala, M.I.K., Tskiris, G.D., Eidmann, K., Meyer-Ter-Vehn, J. & Witte, K. (2004). Influence of the laser prepulse on proton acceleration in thin foil experiments. *Phys. Rev. Lett*. **93**, 045003.

Li, X.Z, Liu, B., Chen, S.I., Wei, Q.M. & Hora, H. (2004). Fusion cross sections in inertial fusion energy. *Laser Part. Beams* **22**, 469–477.

Malekynia, B., Hora, H., Ghoranneviss, M. & Miley, G.H. (2009). Collective alpha particle stopping for reduction of the threshold for laser fusion using nonlinear force driven plasma blocks. *Laser Part. Beams* **27**, 207–215.

Miley, G.H. (1976). *Fusion Energy Conversion*. Hinsdale, IL: American Nuclear Society.

Miley, G., Hora, H., Cang, Y., Osman, F., Badziak, J., Wolowski, J., Sheng, Z.-M., Zhang, J., Zhang, W.-Y. & He, X.-T. (2008). Block ignition inertial confinement fusion (ICF) for space propulsion. *American Institute of Aeronautics and Astronautics*. Paper AIAA 2008-4612, Proceedings of 44th AIAA Joint Propulsion Conference and Exhibit, Hartford, CT.

Moses, E. (2008). Ignition on the National Ignition Facility. *J. Phys. Conf. Ser*. **112**, 012003/1–4.

Moses, E., Miller, G.H. & Kauffman, R.L. (2006). The ICF status and plans in the United States. *J. Phys. IV* **133**, 9–16.

Mourou, G. & Tajima, T. (2002). Ultraintense lasers and their applications. In *Inertial Fusion Science and Applications 2001* (Tanaka V.R., Meyerhofer D.D. & Meyer-ter-Vehn J., Eds.), pp. 831–839, Paris: Elsevier.

Neely, D., Foster, P., Robinson, A., Lindau, F., Lundh, O., Persson, A., Wahlström, C.-G. & Mckenna, P. (2006). Enhanced proton beams from ultrathin targets driven by high contrast ratio laser pulses. *Appl. Phys. Lett*. **89**, 021502.

Nuckolls, J.L. & Wood, L. (2002). *Future of Inertial Fusion Energy*. http://www.ntis.gov.

Oliphant, M. (1989). History of fusion energy. In *DVD Interview with H. Hora*. Canberra: Australian Academy of Science.

Perry, D.M. & Mourou, G. (1994). Terawatt to petawatt subpicosecond laser. *Sci*. **264**, 917–924.

Roth, M., Brambrink, E., Audebert, B., Blazevic, A., Clarke, R., Cobble, J., Geissel, M., Habs, D., Hegelich, M., Karsch, S., Ledingham, K., Neely, D., Ruhl, H., Schlegel, T. & Schreiber, J. (2005). Laser accelerated ions and electron transport in ultra-intense laser matter interaction. *Laser Part. Beams* **23**, 95–100.

Sauerbrey, R. (1996). Acceleration of femtosecond laser produced plasmas. *Phys. Plasmas* **3**, 4712–4716.

Scheffel, C., Stening, R.J., Hora, H., Höpfl, R., Martinez-Val, J.-M., Eliezer, S., Kasotakis, G., Piera, M. & Sarris, E. (1997). Analysis of the retrograde hydrogen boron fusion gains at inertial confinement fusion with volume ignition. *Laser Part. Beams* **15**, 565–574.

Strickland, D. & Mourou, G. (1985). Compression of amplified chirped optical pulses. *Opt. Commun*. **55**, 447.

Szatmari, S. & Schäfer, F.P. (1988). Simplified laser system for the generation of 60 fs pulses at 248 nm. *Opt. Commun*. **68**, 196–201.

Tabak, M., Hammer, J., Glinsky, M.N., Kruer, W.L., Wilks, S.C., Woodworth, J., Campbell, E.M., Perry, M.D & Mason, R.J. (1994). Ignition of high-gain with ultrapowerfull lasers. *Phys. Plasmas* **1**, 1626–1634.

Weaver, T., Zimmerman, G. & Wood, L. (1973) *Exotic CTR fuel: Non-thermal effects and laser fusion application*. Report UCRL-74938. Livermore, CA: Lawrence Livermore Laboratory.

Wilks, S.C., Kruer, W.L., Tabak, M. & Landgon, A.B. (1992). Absorption of ultra-intense laser pulses. *Phys. Rev. Lett.* **69**, 1383–1386.

Yazdani, E., Cang, Y., Sadighi-Bonabi, R., Hora, H. & Osman, F. (2009). Layers from initial Rayleigh density profiles by directed nonlinear force driven plasma blocks for alternative fast ignition. *Laser Part. Beams* **27**, 149–156.

Zhang, P., He, J.T., Chen, D.B., Li, Z.H., Zhang, Y., Wong, L., Li, Z.H., Feng, B.H., Zhang, D.X., Tang, X.W. & Zhang, J. (1998). X-ray emission from ultraintense-ultrashort laser irradiation. *Phys. Rev.* **E57**, 3746–3752.