Investigating the Combustion Energy of the Reaction of Helium Ions Using the Acceleration of Plasma Blocks

V.Markani[1*], N. Azizi[2], M. Amniat talab[3] and R. Nader ali[4]

Abstract– Helium-3 (He3) fusion may also be possible to ignite side-on utilizing petawatt-picosecond laser pulses for uncompressed proton-Boron (HB11) fusion. Interestingly, for the same energy production, HB11 fusion releases a lot less radiation than coal-fired power stations. This method depends on the Chu-Bobin side-on ignition technique, which reduces pre-pulses in order to prevent a phenomenon known as relativistic self-focusing. Theoretical predictions of highly directed plasma blocks with moderate temperatures and extraordinarily high ion current densities exceeding 10^{11} Amps/cm² were confirmed by experiments. The acceleration was caused by a nonlinear force. These results open the door to solid-density fusion's Chu-Bobin side-on ignition. Lastly, a detailed comparison of side-on ignition and standard spherical laser compression is shown to emphasize the essential distinctions in the ignition process.

Keywords: Laser, fusion, radioactivity, plasma blocks, combustion, self-focusing

1. Introduction

The National Ignition Facility (NIF), the most potent laser ever constructed, was completed in 2009, marking a significant advancement in laser-powered fusion. NIF fires laser pulses with energies greater than one million joules (MJ), with a duration of around one billionth of a second [1]. The goal of this project is to use indirect drive to create "spark ignition"[2]. Using this technique, lasers inside deuterium-tritium (DT) fuel capsules are transformed into X-rays. The fuel is compressed and heated by the X-rays to more than 1000 times its initial density. With approximately 10^{19} fusion neutrons produced each laser shot, this intricate process seeks to achieve a gain (ratio of fusion energy out to laser energy in) of 50 to 100 [3]. Scientists have created advanced methods to get around the problems with spark ignition, often known as central ignition. Figure 1 displays previous results, which are positive. They propose that as laser energy increases, the number of fusion neutrons increases almost exponentially. This suggests that 1018 neutrons might be produced by megajoule lasers, which could increase the 10^{12} neutrons produced by kilojoule lasers.

Volume ignition is a further compression method that increases the likelihood of obtaining high neutron yields [4]. This strategy has been supported theoretically by Wheeler mode assessments and simulations that include self-heating caused by neutron generation [5, 6, 7]. Volume ignition is praised for its durability and ease of use, among other qualities [8]. Interestingly, peak fusion yields seen in previous experimental programs [9] seem to correspond exactly with volume ignition theory predictions. These tests offer strong evidence and were carried out at prestigious facilities such Osaka (1986) [10], Livermore (1986) [10], and Rochester (1995) [12], when a record yield of two x 10^{14}neutrons was obtained. If the linear scaling connection holds true, compressing the fuel to a density 1000 times its initial level might result in 1020 neutrons, as seen by the trendline created from these historical data points in Figure 2. Surprisingly, this trendline was established in 1991 [13], four years before to the world record-breaking experiment that took place in Rochester 12. This lucky happenstance offers strong evidence for the viability of volume ignition as a path towards high fusion neutron yields.

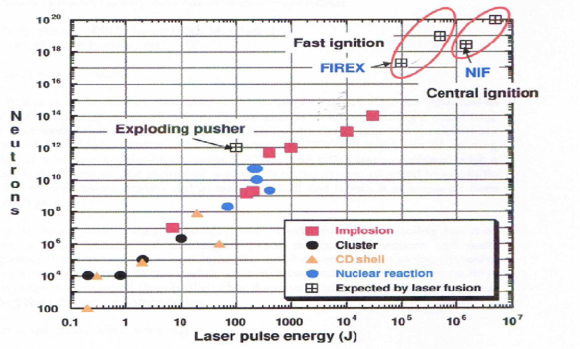

Fig. 1 Measured and projected neutron gains at DT fusion using ignition by spherical laser compression depending on the energy of the laser pulse following Nakai [3].

1* Corresponding Author: Department of Physics, Khoy Branch, Islamic Azad University, Khoy, Iran. Email:vali_markani@yahoo.com
2 Department of Physics, Khoy Branch, Islamic Azad University, Khoy, Iran. Email: nd.azizi460@gmail.com
3 Department of Physics, Faculty of Sciences, Urmia University, P.B. 165, Urmia, Iran.Email: amniattalabmahdi@gmail.com
4 Department of Physics, Faculty of Sciences, Urmia University, P.B. 165, Urmia, Iran.Email: naderrahimali@gmail.com

Received: 2024.04.23; Accepted: 2024.06.11

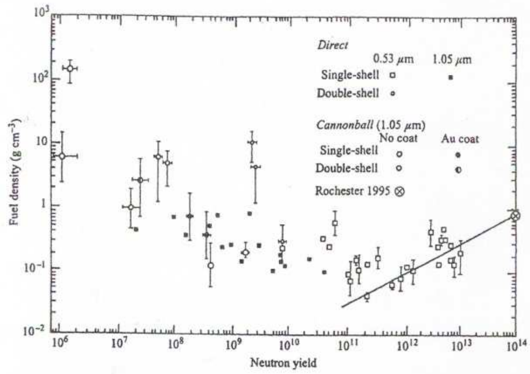

Fig. 2 Measured DT neutron gains from spherical laser compression for direct and indirect drive with single and double shell targets depending on the measured maximum compression, summarized in 1998 [9].

Although extensive experimentation may be required to verify the proposed reactions by complex spark ignition [1], volume ignition presents a possibly faster way to achieve fusion energy. As shown in Figure 2, this technique makes use of carefully planned double-shell compression of target specimens[14]. This method shows promise in achieving notable energy gains more than a factor of 50, even at room temperature. As a result, it might be possible to produce 1019 neutrons per second using the National Ignition Facility (NIF) [15, 16]. This kind of discovery would theoretically make it possible to quickly create a Laser-driven Inertial Fusion Energy (LIFE) prototype by 2020. It is probable that the prototype fusion power plant would make use of solid-state laser drivers pumped by diodes, which are significantly more efficient. With the use of these, a design that is significantly smaller than the National Ignition Facility could be realized. By utilizing the potential of fusion energy, the effective use of this technology would represent a significant and reliable contribution to the mitigation of the climate crisis.

2. Question of very High Fusion Gains

Fuel exhaustion within the reacting pellets is the reason for the limitations of spherical laser compression for Deuterium-Tritium (DT) fusion, which may possibly attain maximum gains (G) of 100 and neutron yields of 10^{20} [11]. If no other options are available, the LIFE project might still provide a workable nuclear fusion energy production solution. Stable helium, the main consequence of fusion, circumvents the hazardous radioactive waste produced by nuclear fission reactors [2]. Although nuclear radiation inside the reactor structure is still a problem, tritium creation and handling in the power plant is far easier to handle than in fission reactors, which may lead to more feasible solutions [2].

Nuckolls and Wood explored the possibility of achieving significantly higher gains, ranging from 100 to 10,000, for laser-driven fusion energy [17, 18]. This study concentrated on a modified fast ignition technique that made advantage of the recently developed petawatt (PW)-class laser pulses with durations of picoseconds (ps) [19, 20]. Early investigations of these pulses' interactions with the target materials revealed surprising relativistic non-linearities. Among these were nuclear transmutations caused by extreme gamma-ray emission, electron and heavy ion acceleration to GeV energies [21], positron production through pair creation, and an exciting possibility for studying B-meson generation and annihilation related to the Large Hadron Collider (LHC) [22]. Furthermore, these exchanges provided opportunities to investigate a number of fresh directions [23, 24].

The two-step scheme proposed by Nuckolls and Wood leverages a sequential laser irradiation process. The first phase consists in compressing the plasma using nanosecond (ns) laser pulses to densities more than 1000 times its initial condition (1000 ns) utilizing standard spherical irradiation techniques. The compressed plasma is then exposed to a petawatt-picosecond (PW-ps) laser pulse, which produces a very powerful electron beam with an energy of about 5 MeV. Then, maybe by chemical implosion, this electron beam initiates a thermonuclear reaction within a sizable volume of DT fuel at a relatively low density (e.g., 10 ns). This strategy provides a regulated way to produce energy in a power plant setting with a targeted repetition rate in the Hz range [19].

Nuckolls and Wood acknowledged several complexities associated with their scheme, including the distinction between volume interaction processes within this method and those discussed in subsequent sections. More research is required to clarify these details as well as those related to the following factors, especially those that examine the alluring possibility of making extraordinarily large profits. Despite these difficulties, NIF's high compression methods—which the LIFE system uses to harness laser fusion—represent a well-thought-out solution. This technology may help avert the impending climate catastrophe by providing a route towards the creation of energy devoid of carbon.

3. One-Step Side-on Laser Ignition

Early propositions by Dean envisioned single-step laser ignition for achieving fusion reactions [25]. This method might facilitate plasma compression with nanosecond (ns) laser pulses, potentially yielding gains within the range of 100 [26]. However, But achieving the more desirable goal of increases over 10,000 [20] still requires a two-step procedure. This method consists of (a) high plasma densities produced by an initial ns compression and (b) a subsequent ps laser pulse that produces the necessary ultra-high energy electron beam for ignition. Unexpected anomalous interaction phenomenon with laser pulses in the petawatt-picosecond (PW-ps) regime may be exploited as a potentially revolutionary route to single-step laser interaction and high gains [21, 22].

Hydraulic simulations were used by researchers to look into this idea more. In order to evaluate the viability of immediately igniting solid-state DT fuel with a laser pulse and doing away with the necessity of Chu and Bobin's side-on compression approach, the simulations concentrated on creating a shock-like fusion flame within the fuel [27, 28]. The outcome disappointed me greatly because ps laser pulses required an energy flux density E* with the threshold Et*.

$$E^* > Et^* = 4 \times 10^8 \ J/cm1 \ for \ DT \quad (1)$$

The first side-on compression system was abandoned in favour of the more practical spherical laser compression scheme because it was more complex and required more laser power than was currently available. But a new set of difficulties emerged with the introduction of extremely short (2 petawatt) laser pulses (half picosecond). The intricate relativistic effects demonstrated by these intense pulses made their practical implementation unfeasible. The identification and subsequent clarification of an aberrant interaction phenomenon was a major advance. Most importantly, the ability to effectively take advantage of this anomaly depended on suppressing pre-pulses to a contrast ratio of greater than 10^8. Researchers successfully eliminated all other confusing relativistic self-focusing effects by establishing this crucial pre-pulse mitigation [29, 30]. The intended plane-wave interaction was realized as a result of this effective mitigation, and this phenomena was later confirmed by comprehensive experimental validation [31]. Specifically, studies examining the interplay between picosecond neodymium glass laser pulses (10^8 W/cm²) in a flat shape demonstrated that nonlinear (ponderomotive) acceleration dominated. Moreover, the resulting accelerated planar fronts' Doppler observations exactly matched previous theoretical and computational predictions [13, 31].

It was proven that there were two highly directed plasma fronts: one going into the target and the other moving perpendicular to the irradiated target [32]. They originated from dramatically enlarged skin layers with dielectric properties [33]. The generated plasma blocks at modest temperature consisted of space-charge quasi-neutral direct ion beams of up to

$$j > j^* = 10^{11} \ Amps/cm^2 \quad (2)$$

or even higher current densities *j*. This made the side-on fusion flame ignition in solid density DT [31] consistent with the Chu-Bobin theory possible again. But given the later discovered impacts of collective (Gabor) stopping power [33, 35] and thermal inhibition [34], this needed to be modified. A proposal to employ ultra-intense ion beams for nuclear fusion using pulsed ps laser pulses with a power output of 10 PW was made earlier [33]. Similar to Nuckolls and Wood's electron-driven laser ignition, gains of up to 10,000 might be possible [19, 20]. Similar to electron beams, a pre-compression of the DT fuel by chemical explosives to roughly ten times the solid state is feasible for side-on driving by the nonlinear force driven plasma blocks with the ultra-high ion current densities of Eq. (2) [19]. Below, we'll talk about how two- or three-dimensional features differ between electron and ion driving.

4. Fusion of He_3-He_3: Nuclear Energy with Negligible Radioactivity

The complexity increase was unexpectedly small, on the order of 10 times, when hydrodynamic simulations of laser-driven side-on ignition from Deuterium-Tritium (DT) fuel to Boron-11 (HB11) were expanded. This is a very different picture from spherical compression fusion, where HB11 ignition is approximately 100,000 times more difficult than DT [36–38]. These results point to the feasibility of employing picosecond laser pulses with power in the several dozen-petawatt range as a greatly simplified laser fusion method for HB11. With this technique, nuclear energy production might become incredibly affordable and eliminate the complicated problems associated with managing radioactive waste that plague traditional nuclear power facilities. Furthermore, the associated nuclear radiation per unit of energy produced would be demonstrably lower than that from coal combustion[39], considering the fuel, the reactor structure, and the final waste product (helium). This discussion warrants further exploration of alternative fusion scenarios that eliminate primary neutron production, such as the helium-3 burning reaction presented in the following section [40]:

$$^3He + {}^3He = {}^4He(1.492MeV) + {}^1H(5.716MeV) + {}^1H(5.716MeV) \quad (3)$$

One possible fuel source for Deuterium-Helium-3 fusion schemes is the harvesting of Helium-3 (He-3) from the lunar surface [41]. Based on these suggestions, the whole U.S. energy requirement for six months may be met by a single Space Shuttle cargo of He-3. Like the Boron-11 (HB11) reaction, Reaction (3) is aneutronic, which means it doesn't generate primary neutrons. On the other hand, when the helium and the 5.716 MeV protons interact, secondary reactions could happen and produce radioactive nuclei. Additional assessment is required due to the relative radioactivity of these secondary reactions in relation to the energy produced per unit of coal burning. However, the expected level of radioactivity is expected to be similar to that of the HB11 case. The characteristic plots in Figure 3 depict the results of hydrodynamic computations performed under identical conditions as those previously employed by Chu [27].

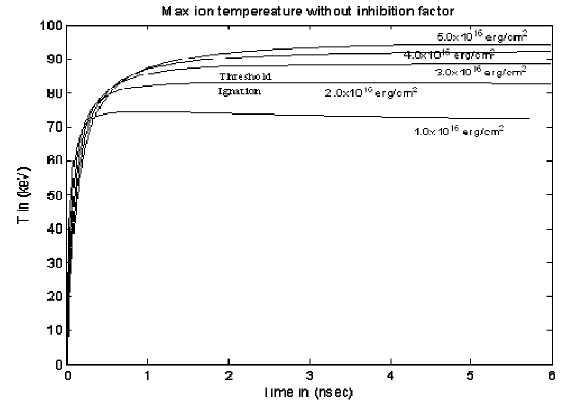

Fig. 3 Computed dependence of the temperature T on time t from hydrodynamics with the assumptions of Chu [27] and Bobin [28] with the input of the energy flux density as parameter.

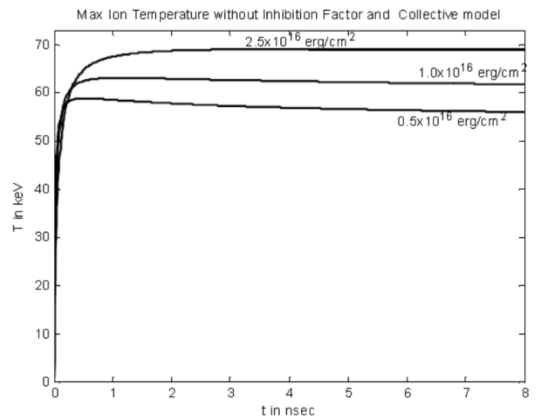

Fig. 4 Computed dependence of the temperature T on time t from hydrodynamics with the all assumptions of Fig. 3, but with modification of thermal conductivity by the inhibition factor [33], and collective model.

Performing the hydrodynamic computations at the same conditions as before by Chu [27], but in this time with inhibition factor and collective model results in the characteristic plots shown in Fig. 4. To find the threshold driver energy flux density one notes that 1×109 J/cm2 does not lead to ignition while 2.5×109 J/cm2 does ignite. By interpolation, the threshold of laser side-on ignition of solid state density He3 has a threshold energy flux density and threshold temperature.

In order to determine the threshold driver energy flux density, one must take note of the fact that 3 × 109 J/cm2 ignites while 2 × 109 J/cm2 does not. The solid-state density threshold of laser side-on ignition is determined by interpolation.He3 possesses a threshold temperature and energy flux density.

$$E_t* = 2.7 \times 10^9\ J/cm^2$$

$$T_t* = 88\ keV,\ for\ He^3\text{-}He^3 \qquad (4)$$

As opposed to earlier, when fusion energy is produced, the bremsstrahlung emission is only offset. To understand the outcome of Equation (4), we are presenting the results [36] here, using the same streamlined circumstances as Chu [27].

$$E_t* = 4 \times 10^9 J/cm^2$$

$$T_t* = 87\ keV,\ for\ HB11 \qquad (5)$$

$$E_t* = 4 \times 10^8\ J/cm^2$$

$$T_t* = 7.2\ keV,\ for\ DT \qquad (6)$$

This shows that, in stark contrast to the ignition using the spherical laser compression technique, both neutron-free reactions (4) and (5) for laser side-on ignition of solid state density are not significantly more complex than DT.

5. Discussion

Although it is still in its early phases of investigation, side-on ignition using nonlinear force-driven plasma blocks promises a promising new avenue for laser-driven fusion energy. Additional investigation could uncover unanticipated difficulties when utilising approaches other than hydrodynamics. Thus, it is imperative to keep a close eye on the proven spherical compression method, made possible by the most potent laser in the world [1,17] and the ensuing LIFE power station project [16]. But since the standard compression method can only achieve increases of about 100 or somewhat higher for Deuterium-Tritium (DT) fuel, it is equally vital to evaluate the possibility of generating gains surpassing 10,000 with the new scheme.

There is a significant conceptual difference between the suggested ion beam method and side-on ignition techniques that use electron beams [31, 36]. The fusion flame is produced via a two-dimensional shock wave technique according to the Chu and Bobin approach [27, 28]. This draws attention to a key distinction between a nuclear flame and a chemical detonation flame, which was previously discussed in-depth [27]. On the other hand, the three-dimensional R criteria must be applied in the case of electron beam interaction [19], taking into account ignition inside a plasma sphere that is bounded by radius R and plasma density. This criterion was derived from numerically calculated optimal fusion gains (G) [13,42] to determine the fusion energy output per unit of input laser energy (Eo) within a spherical volume with radius R containing DT fuel of density (expressed as a multiple of solid-state density s). The formula for G is presented as:

$$G=(E_o/E_{BE})^{1/3}(\rho / \rho_s)^{2/3}=const\times \rho R \qquad (7)$$

In this case, the break-even energy is denoted by E_{BE}, and it is 6 MJ for DT. Equation (7)'s first portion was developed in 1970 [42], while Kidder [43] was the first to publish its second component, which comes from $Eo \sim \rho R^3$. According to the self-similarity model ([13], Section 5), this equation represents the volume burning under spherical uniform compression; however, it is only valid at ideal temperatures (11.5 keV for DT) and for gains G smaller than 8 for DT fuel [44]. Volume ignition for larger gains was found [4] and verified by Wheeler modes [5], which resulted in the development of alternate gain formulas that can be used for higher gain regimes [9, 26, 45].

The ρR formula (equation 7) is limited to three-dimensional geometries under these particular restrictions. A two-dimensional problem by nature, side-on ignition by nonlinear force-driven plasma blocks produces shock fronts as fusion flames [27, 28]. Betti has derived more broad gain formulas that can be used in three-dimensional contexts [45].

Acknowledgments

The authors express their gratitude to the International Atomic Energy Agency (IAEA) in Vienna, Austria, and Islamic Azad University, Khoy Branch, Iran for their collaborative efforts on the Coordinated Research Programme (C.P.R. 13508).

References

[1] E. Moses, G.H. Miller, R.L. Kauffman, The ICF status and plans in the United States,J. de Physique IV 133 (2006).

[2] S. Nakai, Conference Report Prague May 2008, G. Mank and M. Kalaleds, IAEA Coordinated Research Program No. 13011

[3] H. Hora, P.S. Ray, Increased nuclear fusion yields of inertially confined DT plasma due to reheat, Zeitschrift f. Naturforschung 33A (1978) 890-894.

[4] R.C. Kirkpatrick, J.A. Wheeler, The physics of DT ignition in small fusion targets, Nuclear Fusion 21 (1981) 398-401.

[5] X.T. He, Y.S. Li, Physical processes of volume ignition and thermonuclear burn for high-gain inertial confinement fusion, AIP Conf. Proceedngs318 (1994) 334-344.

[6] J.M. Martinez-Val, S. Eliezer, M. Piera, Volume ignition targets for heavy-ion inertial fusion, Laser and Particle Beams 12 (1994) 681-717.

[7] K. Lackner, S. Colgate, N.L. Johnson, R.C. Kirkpatrick, R. Menikoff, A.G. Petschek, Laser interaction and related plasma phenomena, AIP Conference proceedings 318 (1994) 356.

[8] H. Hora, H. Azechi, Y. Kitagawa, K. Mima, M. Murakami, S. Nakai, et al., Measured laser fusion gains reproduced by self-similar volume compression and volume ignition for NIF conditions, J. Plasma Physics 60 (1998) 743-760.

[9] E. Storm, Progress in laboratory high gain ICF, Press conference Lawrence Livermore National Laboratory, 16. Jan. 1986

[10] C. Yamanaka, S. Nakai, Thermonuclear neutron yield of 1012 achieved with Gekko XII green laser, Nature 319, 757 (1986)

[11] J.M. Soures, R.L. McCrory, et al. Direct-drive laser-fusion experiments with the OMEGA,60-beam, >40 kJ, ultraviolet laser system, Phys. Plasmas 3, 2108 (1996)

[12] H. Hora, Plasmas at High Temperature and Densities, 2nd ed., Heidelberg: Springer 1991, Regensburg, Germany 2000.

[13] P. Amendt, H.F. Robey, H.S. Park, R.E. Tipton, R.E. Turner, J.L. Milovich, et al.,
Hohlraum-driven ignition-like double-shell implosions on the omega laser facility, Physical Review Letters 94 (2006) 1-4.

[14] P. Amendt, J.L. Milovich, L.J. Perkins, K.R. Robey, An indirect drive non-cryogenic double shell target driven by a 1Nd laser, IFSA 2009J.Physics – Conf. Ser. (2010) in print

[15] E. Storm, J.F. Latkowski, J.C. Farmer, R.P. Abbott, P.A. Amendt, et al. LIFE—A laser inertial fusion-based approach to high energy production IFSA 2009, J. Physics Conf. Ser. (2010) in print.

[16] E. I. Moses, Edward Teller Lecture 2009, J.Physics – Conf. Ser. (2010) in print.

[17] M. Tabak, J. Hammer, M.N. Glinski, W.L. Kruer, S.C. Wilks, J. Woodorth, et al., Ignition and high gain with ultra powerful lasers, Physics of Plasmas 1 (1994) 1626-1634.

[18] J.H. Nuckolls, L. Wood, Future of Inertial Fusion Energy, Edward Teller Lectures London: Imperial College Press, 2005, pp. 13-14.

[19] J.H. Nuckolls, Grand challenges of inertial fusion energy, J.Physics – Conf. Ser. (2010) in print

[20] G. Mourou, T. Tajima, Inertial Fusion Science & Applications, Elsevier, Paris, 2002, p. 831.

[21] T.E. Cowan, M.D. Parry, M.H. Key, T.R. Dittmire, et al., High energy electrons, nuclear
phenomena and heating in petawatt laser-solid experiments, Laser and Particle Beams,
1999, 773-783.

[22] H. Hora, D.H.H. Hoffmann, Using petawatt laser puses of picosecond duration for detailed diagnostics of creation and decay processes of B-mesons in the LHC, Laser and Particle Beams 26 (2008) 503-505.

[23] T. Tajima, Europ., Prospect for extreme field science, J. Phys. D 55, 519 (2009)

[24] S.O. Dean, The rational for and expanding inertial fusion energy program, J. Fusion Energy 27 (2008) 149-153.

[25] G.H. Miley, H. Hora, Volume Ignition for Single Event Laser fusion by ns-Pulse or PW-ps Block Ignitor, Craig Wuest and Bill Hogan eds (ANS LaGrange IL, 2004) p. 418.

[26] M.S. Chu, Thermonuclear reaction waves at high densities, Physics of Fluids 15 (1972) 413-422.

[27] J.L. Bobin, Laser Interaction and Related Plasma Phenomena, Vol. 4B, New York: Plenum Press, 1974, p. 465.

[28] R. Sauerbrey, Acceleration in femtosecond laser-produced plasmas, Physics of Plasmas 1996 3, 4712 (1996)

[29] H. Hora, J. Badziak, F.B. Boody, R. Höpfl, K. Jungwirth, B. Kralikova, et al., Electromagnetic Waves in Media with Continuously Variable Refraction Index, Optics Commun.,2002207, 333 (2002).

[30] H. Hora, J. Badziak, J.M.N. Read, Y.T. Li, T.J. Liang, Y. Cang, et al., Fast ignition by laser driven particle beams of very high intensity, Physics of Plasmas 14 (7)

(2007) 072701-072701-7.

[31] J. Badziak, S. Glowacz, S. Jablonski, P. Parys, J. Wolowski, H. Hora, Laser-driven generation of high-current ion beams usingskin-layer ponderomotive acceleration,

Laser and Paticle Beams 23 (2005) 401-409.

[32] H. Hora, Laser fusion with nonlinear force driven plasma blocks: Thresholds and dielectric effects, Laser and Particle Beams 27 (2009) 207-222.

[33] M. Ghoranneviss, B. Malekynia, H. Hora, G.H. Miley, X. He, Inhibition factor reduces fast ignition threshold for laser fusion using nonlinear force driven block acceleration, Laser and Particle Beams, 26, 105 (2008)

[34] H. Hora, B. Malekynia, M. Ghoranneviss, G.H. Miley et al. Twenty times lower ignition threshold for laser driven fusion usingcollective effects and the inhibition factor, Appl. Phys. Letters 93 (1) (2008) 011101.

[35] H. Hora, G.H. Miley, M. Ghoranneviss, B. Malekynia, N. Azizi, Laser-optical path to nuclear energy without radioactivity: Fusion of hydrogen–boron by nonlinear force driven plasma blocks, Optics Communic. 282 (2009) 4124-4126.

[36] H. Hora, G.H. Miley, N. Azizi, B. Malkynia, M. Ghoranneviss, X.T. He, Nonlinear force driven plasma blocks igniting solid density hydrogen boron: Laser fusion energy without radioactivity, Laser and Particle Beams 27 (2009) 491-496.

[37] H. Hora, G.H. Miley, M. Ghoranneviss, B. Malekynia, N. Azizi, X. Tu, Fusion energy without radioactivity: laser ignition of solid hydrogen–boron (11) fuel, He. Energy and Environmental Science 3 (2010) 479-486.

[38] T. Weaver, G. Zimmerman, L. Wood, Exotic CTR Fuel: Non-Thermal Effects and Laser Fusion Application, Report UCRL-74938, 1973.

[39] Ron McNally, Oak Ridge Nat. Lab. Report NSIGUDAT 14 Sept. 1987

[40] G.L. Kulcinski, Fife minutes contribution about harvesting helim-3 from the moon for energy production, CNN-TV World News, Nov. 19, 2007.

[41] H. Hora, Translation National Research Council Canada NRC-Technical Translation TT-1193, InstitutFürPlasmaphysik, Garching Report 6/23, 1964.

[42] Hora and D. Pfirsch, Influence of Fast Ion Losses in Inertially Confined Nuclear Fusion Plasma, Laser Interaction and Related Plasma Phenomena (H. Schwarz and H. Hora, eds.),Plenum, New York, 1972, Vol. 2, 515.

[43] R.E. Kidder, Laser compression of matter: optical power and energy requirements, Nuclear Fusion 14, 797 (1974)

[44] H. Hora, Volume Ignition in Pellet Fusion to Overcome the Difficulties of Central Ignition, Z. Naturforschung42A, (1987) 1239-1240.

[45] R. Betti, Edward Teller Lecture, IFSA 2009, J. Phys.-Conf. Ser. (2010) in print.