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# Extreme CPA-Laser Pulses for Environmentally Clean Laser Boron Fusion

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Abstract:
The Chirped Pulse Amplification CPA – which discovery was highlighted by the 2018 Physics Nobel Prize to Gerard Mourou and Donna Strickland – reached such an extreme ultrahigh power level that the ignition of controlled fusion reactions in a reactor is possible without needing thermal pressures with dozens of million degrees centigrade. In contrast for avoiding the extreme temperatures, non-thermal pressures driven by the nonlinear force for ultrahigh picosecond acceleration of plasma blocks are to ignite the environmentally clean, safe and low cost fusion of hydrogen with the abound boron-11 isotope.

Why are many dozens of billion dollars invested since 60 years in research for a fusion power reactor "but why does it always seem to be 30 years away" [1]? The need for the fusion energy reactor is an important option for electric energy generation in contrast to burning carbon from the present level. It has to be below the level of 1960 needing a reduction to less than 20% of the present carbon emission. The attraction of fusion energy is given by the fact that the nuclear reaction energy is about ten million times higher than the chemical energy from burning coal. The problem however is that the temperature of chemical burning is few hundred degrees C and the nuclear burning needs temperatures in the range of hundred million degrees.

60 years research was needed to nearly master these astronomic temperatures in the laboratory. The reaction of hydrogen nuclei into helium in the center of the sun is at 15 million degrees. Equilibrium temperatures for fusion of deuterium in a Wendelstein-stellarator reached 10 million degrees (about 800 eV) in 1980 [2] (see Chapter 2.6 of [3]) that now was increased by a factor four [4]. These high temperatures were about for aiming a continuously working extremely low density DT fusion reaction in a toroidal magnetic confinement in the JET-tokamak experiment [5] working at the high temperature conditions. To reach a positive energy gain the aim is in the ITER experiment with DT fusion in the year 2037 to achieve an eight minutes run [6]. Alternatively, inertial confinement of controlled micro-explosions for a reactor using nanosecond laser pulses for ignition in the NIF experiment at solid state or much higher plasma densities did reach similar temperatures [7] but none has yet arrived at the conditions of break-even for a reactor.

These fusion reactions are using the usual gas-dynamic plasma pressures p given by the density and very high temperature T. Can one have other non-thermal pressures? Let us look to other pressures [3][8] with conditions of nonlinearities [9][10][11], different form LTE (local thermal equilibrium) or of non-ideal plasmas [12] or laser-fusion during especially short picosecond times (about 1000 times shorter than NIF) for laser-plasma ignition. The nonlinearities were evident [13] and may lead to solve the problem [14][15].

The alternative way for igniting a fusion reaction not by thermal pressures p but by non-thermal pressures was given by the nonlinear interaction of laser irradiation with plasmas [8] for the equation of motion for the force density

$$\mathbf{f} = -\nabla p + \mathbf{f}_{NL} \qquad (1)$$

$\mathbf{f}_{NL}$ represents the forces due to electric and magnetic fields **E** and **H** of a laser pulse of frequency $\omega$ in the plasma with a plasma frequency $\omega_p$ and a refractive index **n**. These fields are force quantities and are determining the force in the plasma in quadratic form as result of electromagnetic laser irradiation and are the gradients of the Maxwellian stress tensor

$$\mathbf{f}_{NL} = \nabla\bullet[\mathbf{EE}+\mathbf{HH}-0.5(\mathbf{E}^2+\mathbf{H}^2)\mathbf{1}+(1+(\partial/\partial t)/\omega)(\mathbf{n}^2-1)\mathbf{EE}]/(4\pi)-(\partial/\partial t)\mathbf{E}\times\mathbf{H}/(4\pi c) \qquad (2)$$

where **1** is the unity tensor. This expression of Eq.(2) defines the final, general, Lorentz and gauge invariant transient formulation of the equation of motion in a plasma of Eq. (1) in the presence of a laser pulse including dielectric optical response [8]. At plane wave geometry, the nonlinear force of Eq. (2) can be reduced to [8] with the electric field amplitude of the irradiated laser pulse $E_v$

$$f_{NL} = -(\partial/\partial x)(\mathbf{E}^2+\mathbf{H}^2)/(8\pi) = -(\omega_p/\omega)^2(\partial/\partial x)(E_v^2/\mathbf{n})/(16\pi) \qquad (3)$$

while general cases need all tensor components of Eq. (2) [16].

This type of force in electrostatics was discovered by Thomson [17] as ponderomotion. The beginning of electro-dynamics was Coulomb´s realizing of the kind of Newton’s forces between electric charges to be linear by the electric field **E** as a force quantity. A basically different electric force in (3) is without charges [17]. It is given by the square of the force quantity **E** but with inclusion of the dielectric response or refractive index, not only for statics, also for time dependent fields, generalized through Maxwell’s equations for magnetic fields **H**, and expressed by Maxwell’s stress tensor and the physics of plasmas developed later since 100 years ago. This is why Eq. (2) is a nonlinear force [8][9][10][11].

The computation result of Fig. 1 of 1977 was performed with similar parameters as the measurements of Sauerbrey 1996 [18] that were possible only after the CPA laser pulses [19] of 0.3ps duration were available. The ultrahigh acceleration above $10^{20}$ cm/s$^2$ can be seen directly from Fig.1 how within 1.5 ps, the laser intensity could accelerate the plasma block moving against the incident laser light as later measured by Sauerbrey [18] from the blue Doppler shift of spectral lines in the plasma moving against the direction of the laser light. This was the first measurement of nonlinear force driven plasma block acceleration. The computation included the most general thermal (collisional) heating of the plasma but this was not pronounced. Thermal acceleration with comparable nanosecond laser intensities were more than four orders of magnitudes lower. The ultrahigh nonlinear force acceleration was repeated [20] in exact agreement with the computations. The necessary condition was that the laser pulses had a very high quality contrast ratio similar to comparable experiments [21][22] where a most extreme experimental technology could show [23] how the usually appearing relativistic self-focusing [24] had to be suppressed.

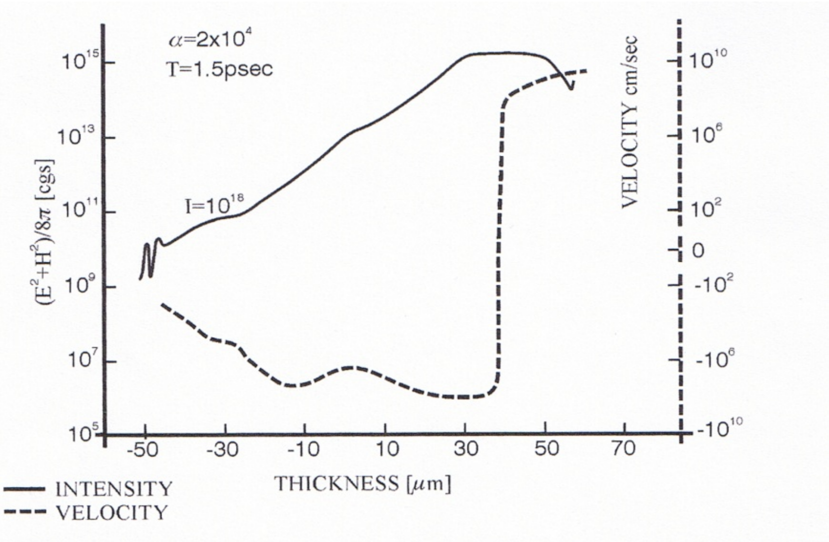

*FIG. 1. $10^{18}$ W/cm$^2$ neodymium glass laser is incident from the right hand side on an initially 100 eV hot 100 $\mu$m plasma slab with initially low reflecting bi-Rayleigh density profile at initial time t=0, resulting at time t=1.5 ps of interaction in a velocity distribution* v(x) *on the depth x and in an energy density of the laser field* $(\mathbf{E}^2+\mathbf{H}^2)/8\pi$. *The dynamic development had accelerated the plasma block of about 20 vacuum wave length thickness of the skin layer moving against the laser and another block into the plasma showing ultrahigh* $>10^{20}$*cm/s*$^2$ *dielectric acceleration by the nonlinear force (figure 10.18a&b of [10], summarized in Fig 8.4 of [11]).*

The plasma block acceleration of picosecond laser pulses for measuring the fusion reaction was clearly demonstrated in deuterium targets [25] with picoseconds laser pulses, Fig. 2. This resulted in 10,000 times higher fusion gains at low plasma temperature by block acceleration in the target [26] in contrast to the numerous fusion measurements under heating at thermal equilibrium conditions, Fig. 2. Compared with the numerous measurements at varying laser pulse duration, The measurements [25] N98 and B06 were with same ps laser pulses of same power, however the measurement of Norreyes et al., N98, were with extremely high contrast ratio for producing block generation with the 10,000 times higher fusion gains in contrast to B06 with usual pulses working at thermal equilibrium conditions. In the first case, the 10,000 times increased neutron gain at measured exceptionally low temperature confirms the expected plasma block generation.

Computations with ps energy deposition on plane solid deuterium-tritium fusion targets resulted in the threshold for ignition needing an energy flux of $10^8$ J/cm$^2$ [27]. These computations were updated [28] and when instead of the DT fusion that of hydrogen H with the boron isotope 11 (HB fusion) was used - resulting in equal energetic helium (alpha particles)

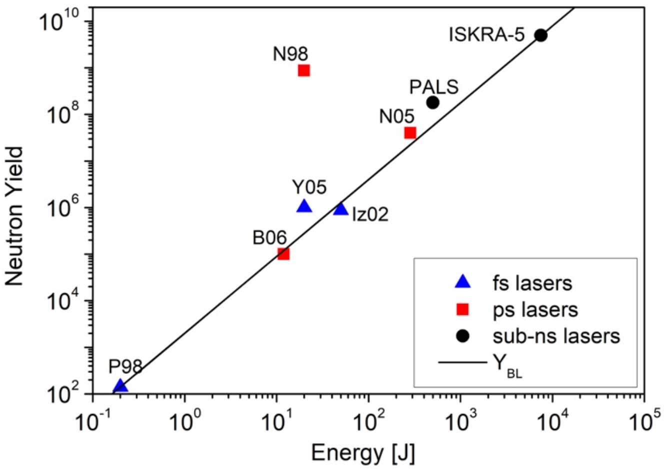

*Fig. 2.,Compilation of emission of fusion neutron gains from deuterated targets irradiated by laser pulses of varying energy and varying pulse duration [25]. At thermal equilibrium interaction, the results were on a line but the result with picoseconds pulses N98 with non-thermal block acceleration were increased by a factor 10,000 against the thermal equilibrium cases.*

$$H + {}^{11}B = 3\,{}^{4}He + 8.7\,\text{MeV}, \qquad (4)$$

a surprising result turned out [29]. It was well known that HB11 fusion under thermal equilibrium had about 5 orders of magnitudes lower energy gains than DT at classical thermal equilibrium conditions, see Section 9.5 of [11]. This was considered as too low for a fusion reactor. However if the non-thermal ps-plasma block ignition was used in the calculation, the gains were nearly five orders of magnitudes higher than classical [29] though the computations were pessimistically only using binary reactions like DT. When measurements of HB11 reactions resulted in billion times higher fusion gains [30] first estimations [14] included the three-fould alpha multiplication, Eq. (4) based on preceding computations [31] using the genuine two fluid hydrodynamics [32]. A detailed analysis of the avalanche reaction by inclusion of the elastic nuclear collisions between the nuclei resulted in an increase of the gains by four order of magnitudes [33]. Adding this increase by four magnitudes to the five orders from the block mechanism [29] the measured billion times higher gains than classical have been explained.

The design of an environmentally clean, safe, comparably fast available boron fusion reactor for low cost electricity was possible [14]. Finally the generation of about 10,000 times less neutrons by secondary reactions than produced per alpha particles can be controlled such that the generated radioactivity is below the level [34] needed for an environmentally clean operation of the reactor.

As a consequence, the design of a spherical HB11 fusion reactor was given, see Fig. 16 of [14], where the solid density fuel had to be in cylindrical form and the reaction is trapped by the recently produced ultrahigh kilotesla magnetic fields produced [13] by capacitor coils at irradiation of kJ nanosecond laser pulses. The end-on initiation of the fusion reaction in the cylinder needs picoseconds CPA-laser pulses [19] of more than 30kJ energy. These types of lasers are close to be on the market with minute repetition time and shorter producing 277 kWh of electricity per shot from burning 14 milligrams of boron [15].

Acknowledgement.
This work is the result of research for laser driven fusion going back to the initiations by Edward Teller and Andrei D. Sakharov [35][36][37] with first publications [38][39]. The opening of the nonlinear Physics by the laser was essential [8] (see Feynman, Chapter 6.3 of [11]) last not least by specific team work [14][15][40][41] where not only the fulminant discovery of the CPA-laser pulses was essential. Furthermore contributions by Gerard Mourou were involved for designing of a ground-breaking new fusion reactor [14][31] leading to some commercialization by the "HB11 Fusion Pty.Ltd.". Collaboration is gratefully acknowledged to S. Eliezer and N. Nissim (SOREQ, Israel), J. Krasa (ASCzR), E.M..Campbell (U Rochester), R. Sauerbrey (HZ Dresden), P. Lalousis (FORTH Heraklion) and W. McKenzie, J. Kirchhoff, G. Kirchhoff (HB11 Energy).

References:

[1] M. Windridge, Ignition pending: Why does fusion always seem to be 30 years away? Physics World 31 No.10 October (2018) 55
[2] G. Grieger, and Wendelstein Team. Measurements at the Wendelstein Stellarator. Plasma Physics and Controlled Fusion Research, Proceedings IAEA Vienna, Vol. 1 (1981) pp. 173 and 185 (1981)
[3] H. Hora. Plasmas at High Temperature and Densities. Springer Heidelberg 1991
[4] A. Dinklage, C.D. Bendler, P. Helander. Magnetic configuration effects on the Wendelstein 7-X stellarator. Nature Physics 14 (2018) 1067
[5] M. Keilhacker, A. Gibson, C. Gormeyano. High Performance from Deuterium-tritium plasma Nuclear Fusion 39 (1999) 2137
[6] B.J. Green, The Status of ITER – the fusion reactor development project. Australian Physics 55 (2018) 131
[7] O.A. Hurricane, D. A. Callahan, D. T. Casey, P. M. Celliers, C. Cerjan, E. L. Dewald, T. R. Dittrich, T. Döppner, D. E. Hinkel, L. F. Berzak, L.F.B. Hopkins, J. L. Kline, S. Le Pape, T. Ma, A. G. MacPhee, J. L. Milovich, A. Pak, H.-S. Park, P. K. Patel, B. A. Remington, J. D. Salomonson, P. T. Springer & R. Tommasini. Fuel gains exceeding unity in an inertal confinement fusion implosion Nature 506, (2014) 343
[8] H. Hora, Nonlinear Confining and Deconfining Forces Associated with the Interaction of Laser Radiation with Plasma, Phys. Fluids 12, (1969) 182
[9] H. Hora, H., Nonlinear Effects and Nonthermal Plasmas. Nuclear Instruments and Methods A271 (1988) 117
[10] H. Hora, Physics of Laser Driven Plasmas, Wiley, New York 1981
[11] H. Hora, Laser Plasma Physics, Second Edition SPIE Books, Bellingham WA (2016)
[12] D.H.H. Hoffmann, H. Hora, S. Eliezer, V.E. Fortov, N. Nissim, P. Lalousis, J.-M. Martinez-Val. Non-ideal plasma at elastic nuclear collisions for avalanche boron fusion. European Conference on laser interaction with matter ECLIM. Sept. Moscow (2016)

[13] P. Lalousis, H. Hora and S. Moustaizis, Optimized boron fusion with magnetic trapping by laser driven plasma block initiation at nonlinear force driven ultrahigh acceleration. Laser and Prticle Beams 32 (2014) 411

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

[15] H. Hora, S. Eliezer, G.J. Kirchhoff, N. Nissim, J.X. Wang, P. Lalousis, Y.X. Xu, G.H. Miley, J.M. Martinez-Val, W. McKenzie, J. Kirchhoff. Road Map to Clean Energy Using Laser Beam Igntion of Boron-Hydrogen Fusion. Laser and Particle Beams, 35, (2017) 730

[16] L. Cicchitelli, H. Hora and R. Postle. Longitudinal Field Component of Laser Beams in Vacuum Physical Review A41 (1990) 3727

[17] W. Thomson (Lord Kelvin) Cambridge and Dublin Mathematical Journal, November (1845)

[18] R. Sauerbrey. Acceleration of femtosecond laser produced plasmas. Physics of Plasmas 3 (1996) 4712

[19] D. Strickland, G. Mourou. Compression of amplified chirped optical pulses. Opt. Comm.65 (1985) 219

[20] I. Földes, J.S. Bakos, K. Gal, Y. Juhasz, M. A. Kedves, G. Koscis, S. Szatmari, G. Verex. Properties of high Harmonics generation by UV laser pulses on solid surfaces. Laser Physics 10 (2000) 264

[21] J. Badziak, A.A. Kozlov, J. Makowski, P. Paris, L. Ryz, J. Wolowski, E. Woryna, & A.B. Vankov. Investigation of ion streams emitted from plasma produced with a high power picoseocond laser. Laser and Part. Beams 17 (1999) 323

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

[23] M. Zhang, J.T. He, D.B. Chen, Z.H. Li, Y. Zhang, L. Wang., B.L. Feng, D.F. Zhang, X.W. Tang and J. Zhang. Effects of a prepulse on γ-ray radiation produced by a femtosecond laser with only 5-mJ energy. Phys. Rev. E 57 (1998) 3745

[24] H. Hora, Theory of Relativistic Self-Focusing of Laser Radiation in Plasmas. J. Opt. Soc.of America 65 (1975) 882.

[25] J. Krasa, D. Klir, A. Velyhan, D. Margarone, E. Krousky, K. Jungwirth, J. Skala, M. Pfeiffer, J. Kravarik, P. Kubes, K, Rezac and J. Ullschmied. Observaion of repetive bursts in emission of fast ions and neutrons in sub-nanosecond laser-soid experiments. Laser and Particle Beams 31 (2013) 395

[26] P.A. Norreys., A.P. Fews F.N. Beg, A.R. Bell, D.A. Dangor, P. Lee, M.B. Neslon, H. Schmidt, M. Tatarakis and M.D. Cable. Neutron production from picosecond laser irradiation of deuterated targets at intensities of $10^{19}$ W/cm$^2$. Plasma Phys. Contr. Fusion 40 (1998), 175

[27] M.S. Chu. Thermonuclear reaction waves at high densities. Phys. Fluids 15 (1972) 412

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

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

[30] A. Picciotto, D. Margarone, A. Velyhan, P. Bellini, J. Krasa, A. Szydlowski, G. Bertuccio, Y. Shi, A. Margarone, J. Prokupek, A. Malinowska, E. Krouski, J. Ullschmied, L. Laska, M. Kucharik

G. Korn. Boron-proton nuclear-fusion enhancement induced in boron-doped silicon by low contrast pulsed. Phys. Rev. X4 (2014) 031030,

[31] P. Lalousis, H. Hora, S. Eliezer, J.M. Martinez-Val, S. Moustaizis, G.H. Miley & G. Mourou. Shock mechanism by ultrahigh laser accelerated plasma blocks in solid density targets for fusion. Physics Letters A, 377 (2013) 885

[32] H. Hora, P. Lalousis, S. Eliezer. Analysis of the Inverted Double Layers in Nonlinear Force Produced Cavitons at Laser-Plasma Interaction. Phys. Rev. Letters 53 (1984) 1650

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

[34] H. Hora, S. Eliezer and N. Nissim, Elimination of neutrons from nuclear reactions in a reactor especially clean laser boron 11 fusion without secondary waste. International Patent Application No. PCT/EP2018/082520 (priority 27 November 2017)

[35] Edward Teller Lectures, H. Hora and G.H. Miley Editors, Imperial College Press, London 2016

[36] E.M. Campbell, Foreword to [35]

[37] J.H. Nuckolls, Edward Teller Medal Acceptance Award (LIRPP), see [35] p. 85

[38] N.G. Basov, Comments on the History and Prospects of Inertial Confinement, see [35] p. 89

[39] H. Hora, Estimations for heating of a plasma with lasers, Institute of Plasma Physics, Garching, IPP/6/23, July 1964. Technical Translation 1193 (National Research Council of Canada, Ottawa, 1965)

[40] H. Hora, R. Castillo, R.G. Clark, E.L. Kane, V.F. Lawrence, R.D.C. Miller, M.F. Nicholson-Florence, M.M. Novak, P.S. Ray, J.R. Shepanski, and A.I. Tsivinsky, Calculations of Inertial Confinement Fusion Gains Using a Collective Model for Reheat, Bremsstrahlung and Fuel Depletion for High-Efficient Electrodynamic Laser Compressions. Proceedings of the 7th IAEA Conf. Plasma Phys. and Thermonucl. Fusion, Innsbruck, 23-30 August, 1978 (IAEA Vienna)], Vol. III (1979) p.237.

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