Shock Studies in Nonlinear Force Driven Laser Fusion with Ultrahigh Plasma Block Acceleration

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Abstract: High intensity picoseconds laser pulses transfer energy directly into kinetic energy of plasma blocks without thermal losses, without delays by collisions and with exclusions of most instabilities. Following the long known theory of the nonlinear (ponderomotive) force, the plasma receives an ultra-high acceleration first measured by Sauerbrey and confirmed in all details based on preceding theory. Interaction of the plasma blocks with solid state fusion fuel should generate a Chu-Bobin flame. Using hydrodynamics with separate electron and ion fluids, first detailed properties can be studied about shock generation, the varying velocity of the flame fronts and the internal electric fields.

Key words: Inertial confinement; picoseconds laser pulses; non-thermal energy conversion, non-linear simulations, aneutronic fuel;

1. Introduction

A basic difference for fusion energy generation was opened with the use of Petawatt-picosecond (PW-ps) laser-plasma interaction [1] initiated since 1988 [2] in contrast to laser driven spherical compression and thermal ignition (CATI) needing more than 1000 times solid state densities deuterium-tritium (DT) when using nanosecond laser pulses [3] and where a breakthrough is expected [4]. In contrast to these thermal processes with unavoidable losses, delays, inefficiencies and instabilities, the new option with PW-ps pulses uses the efficient direct conversion of laser energy into motion of plasma blocks where the thermal processes are nearly fully avoided. The direct conversion of laser energy by the nonlinear force into motion of plasma blocks (DICNOF) was evident after dielectric properties of plasmas with optical constants into the Maxwellian stress tensor was introduced permitting the generalizing of the ponderomotive force up to the nonlinear force [5] for explaining measured MeV ion energies at laser-plasma interaction including self-focusing [6]. Computations of plane geometry interaction of ps laser pulses with 10^{18}W/cm^2 laser pulses arrived at ultra-high accelerations of plasma blocks above 10^{20}W/cm^2 (Fig. 10.18b of Ref. [6]) within picosecond interaction, clearly demonstrating that the well included general thermal processes were of very minor influence.

These ultra-high accelerations were first measured by Sauerbrey [7] where the values of 2×10^{20}cm/s^2 were in perfect agreement with the theory by inclusion of dielectric swelling [8]. These accelerations were reproduced [9] and were up to fife orders of magnitudes higher than the measured acceleration by thermal pressures using nanosecond laser pulses. The essential necessity was providing contrast ratios above 10^8 for suppression of relativistic self-focusing when using <ps laser pulses. This was supported by other independent measurements [10][11] where plane wave front interaction was verified for confirming interaction with dielectrically increased skin layers [12].

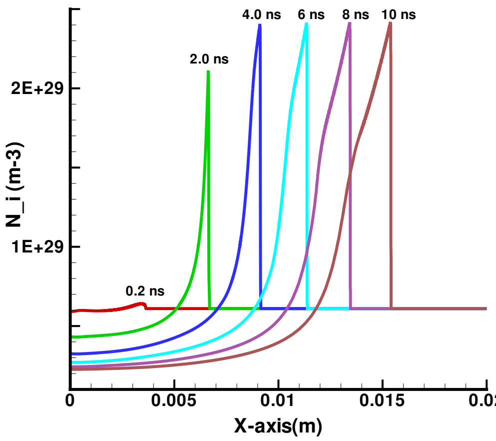

Fig. 1. Ion densities N_i depending of the depth X after a one ps 3×10^8 J/cm^2 laser pulse of 248 nm wave length has irradiated solid density DT. Parameter is the time after the ps interaction

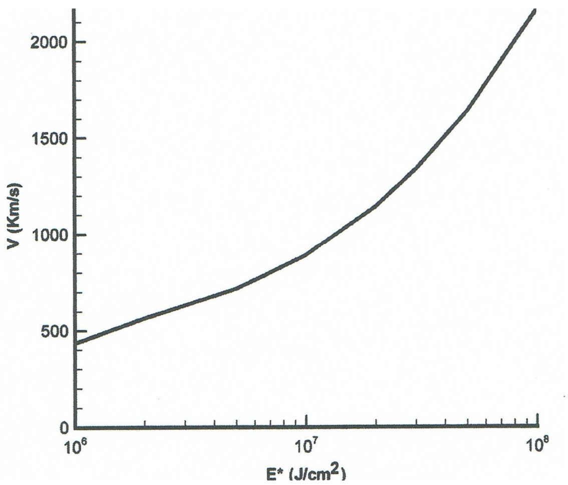

Fig. 2. Velocity V of the fusion flame at 2 nanoseconds after the initiating ps laser pulse of 248 nm wavelength depending on the energy flux E*.

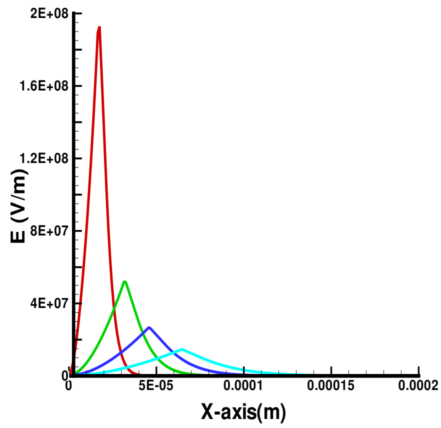

Fig. 3. Longitudinal electric field E as in case of Fig. 1 for E* = 10^8 J/cm^2 depending of the depth X at times of 40ps; 400ps; 1ns; 2 ns from the highest maximum respectively.

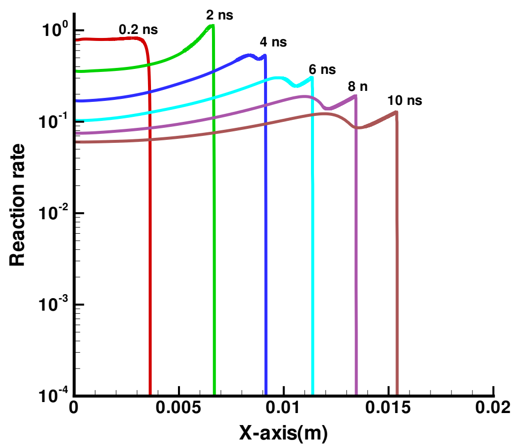

Fig. 4. Reaction rates (to be multiplied by 10^{36} m^{-3}s^{-1}) in solid DT at 1 ps pulse of energy flux E*= 3×10^8 J/cm^2 KrF laser irradiation depending on the fuel depth x at different times up to 10 ns.

2. Genuine Two-fluid Hydrodynamic Computation of Shock Generation

The plasma blocks after ultra-high acceleration driven by the nonlinear force from ps very intense laser pulses could be used for the Chu-Bobin ignition of a fusion flame by side-on ignition of uncompressed DT where plane wave laser interaction with an energy flux density E* of 10^8J/cm^2 was necessary [13]. These computations used one-fluid hydrodynamics of Chu's with an updating was necessary for the later known reduction of the thermal conduction by an inhibition factor based on the electric double layer between the hot flame and the DT fuel. Further, the stopping power had to use the Gabor collective model at this high plasma densities and not the Bethe-Bloch binary collision model. After this updating, the ignition thresholds for the fusion flame arrived at up to 20 times lower values [14].

Application of the genuine two-fluid hydrodynamics for showing the very high internal electric fields in the plasma [15][16] were disclosed leading to many more details of the flame propagation in solid DT after the ps laser interaction and the later development of a shock process [17]. Using the same parameters for the generation of ps ultra-high accelerated plasma blocks of about a 5 micrometer depth moving into solid density DT, we are presenting here further here reported results following the initial computations [17].

Fig. 1 shows ion densities with shock profiles moving at the interaction edge into the solid density DT. A shock structure shows maximum densities four time the solid state as it is the result of the Rankyne-Hugoniot simplified analytical model. The shock thickness is increasing on time what could be covered only by complete inclusion of thermal and plasma collision properties in our computation [15][16][17]. It is interesting that the shock is pronounced only very late after 2 ns being only little visible at 200 ps. It should be mentioned that the same plots for three times lower E* values shows an about two times earlier building up of the shock. The shock velocity was evaluated for varying E* and resulted in Fig. 2 at 2 ns. It can be seen that the fast increasing velocity at E* of 10^8 J/cm^2 is reaching values higher than 2000 km/s with convincing ignition properties. In order to understand the reasons for the long (> 200 ps) delay of the shocking process, we show in Fig. 3 the longitudinal electric field which can be seen only form the genuine two-fluid hydrodynamics. It is remarkable that during the very first few hundred picoseconds after the laser pulse in the phase of the establishing the shock front, the electric field is rather high and decays only at 2 ps to comparably low values when the shock is nearly fully developed (Fig. 1).

3. Decrease of Flame Velocity and Relativistic Block Studies

The studies with the genuine two-fluid hydrodynamics permits an evaluation about the decreasing velocity of the front of the fusion flame at the very long times of nanoseconds after the ps initiation of the flame. Fig. 4 shows results of fusion reaction rates with a one ps laser pulse of E*=10^8 J/cm^2. The velocity of the fusion flame is decreasing from 2,130 km/s at 2 ns to 1,070 km/s at 10 ns and the values of the reaction rates decay faster than in the case with only three times higher irradiation. Nevertheless, the fusion gains are not very much lower, going down at 10 ns. The gains at the time of 2 ns are nearly the same. The result of the ion density at the flame front has reached nearly the Rankine-Hugoniot value of four times compression earlier at 2 ns than in the case with three times higher irradiation of Fig. 1.

The fact of the growing thickness of the compression range on time may be understood by the thermal mechanisms around the fusion flame with a stronger effect at the first case with the higher energy flux. This can also be understood that the shock compression in the early stage are within a too thin area such that the thermal mechanisms - completely covered by the code – are causing a dissipation of the too thin compression areas.

We may conclude that the earlier studied mechanisms of shock ignition [18] for fusion as evaluated for longer ns pulses is supported by our results at least for these longer times [17]. This supports the results of shock wave ignition for fusion [19] which requires a long (few ns) and high energy laser pulse. The high pressure (P) shock wave thickness (d) in the nanosecond interaction case is estimated from the equality of pressures at the interface between a flyer (or a plasma block with density ρ_0 and flow velocity u_0) and the compressed target (the nuclear fuel: DT or pB11, etc with density ρ_C and flow velocity u_C). Since $P \sim \rho_0 u_0^2 \sim \rho_C u_C^2$ and the shock wave transition time in the flyer with a thickness l is $t = l/u_0$ one gets a shock wave thickness d of the order $d \sim (\rho_0/\rho_C)^{1/2}\ l$. In this purely shock ignition scheme [18] – in contrast to the here studied picosecond plasma block ignition – the nanosecond case values are $(\rho_0/\rho_C) \sim 0.001$ and $l \sim 1\mu m$ implying $d \sim 0.03\ \mu m$. The ignition criterion is based on the requirement that the alpha particles created in the DT reaction are reabsorbed in the hot spot implying a "ρR" value larger than 0.3 g/cm^2 for a temperature about 10 keV and larger values for higher temperatures. In the shock wave ignition "ρR" = $\rho_C d \sim l(\rho_0\rho_C)^{1/2} \sim 0.003$ g/cm^2 for our case which is two order of magnitude too low. This result fully explains why the ns interaction scheme for shock ignition [18] is basically different from the ps laser pulse initiated block ignition scheme.

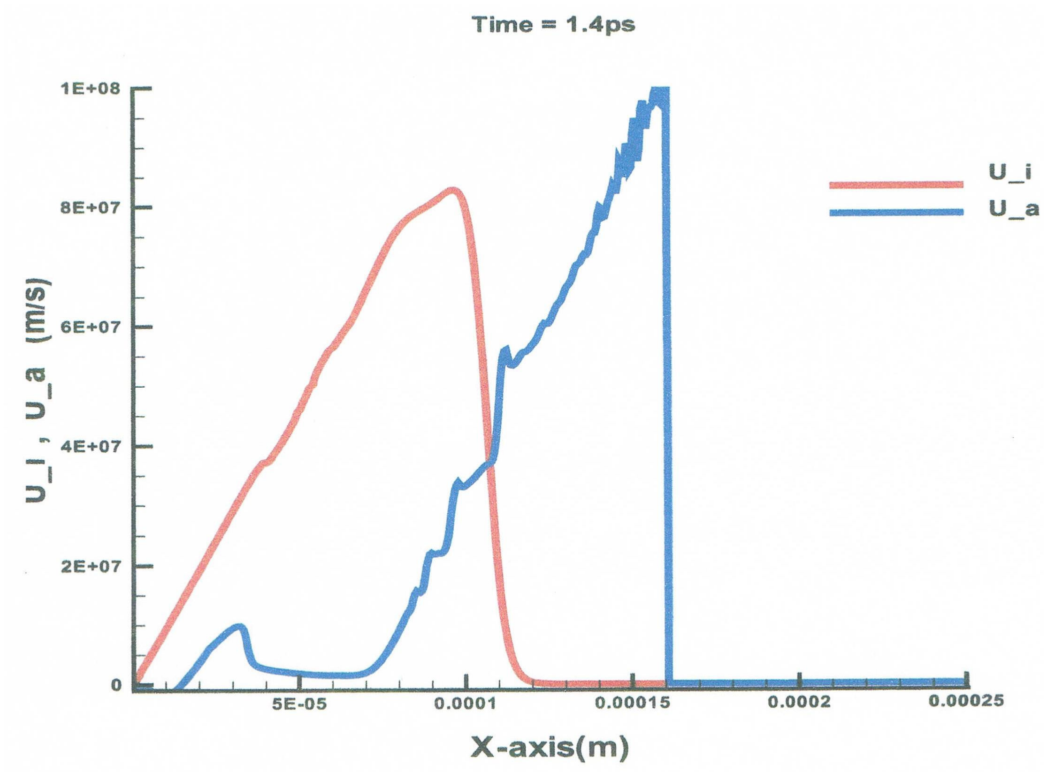

Fig. 5. Irradiation of a 0.5 ps 248 nm wave length long laser pulse of 10^{21} W/cm^2 on solid DT. Ion velocity U_1 and velocity of the alpha particle fluid depending on depth X in the target at time 1.4 ps.

It is of interest to combine the here presented results and those of [17] with fusion at lower E* values, for comparison with fusion reactions similar to the ns processes of impact fusion [20]. With the hear covered early results of few hundred ps or less, we could see how fusion reactions are well appearing as expected from impact fusion as measured [20] but no sustainable ignition was achieved for which the ps flame production needing higher E* values.

Following relativistic conditions [21] one can see the very high plasma block acceleration using 10^{21} W/cm^2 0.5 ps laser irradiation in Fig. 5. The ion block for DT reaches then 70 MeV directed ion energies and the ultra-high acceleration is 1.6×10^{22} cm/s^2. The measurement of total conversion of laser energy into 29 nm thick diamond layers [22] can be explained as an absorption process by nonlinear force acceleration with ultra-high acceleration [23].

4. Application to Laser Driven Fusion

Petawatt-picosecond (PW-ps) laser pulses open a basically new approach for igniting solid density (or modestly compressed) fusion fuel to ignite high energy gain reactions. The direct conversion of laser energy by the nonlinear force into motion of plasma blocks (DICNOF)

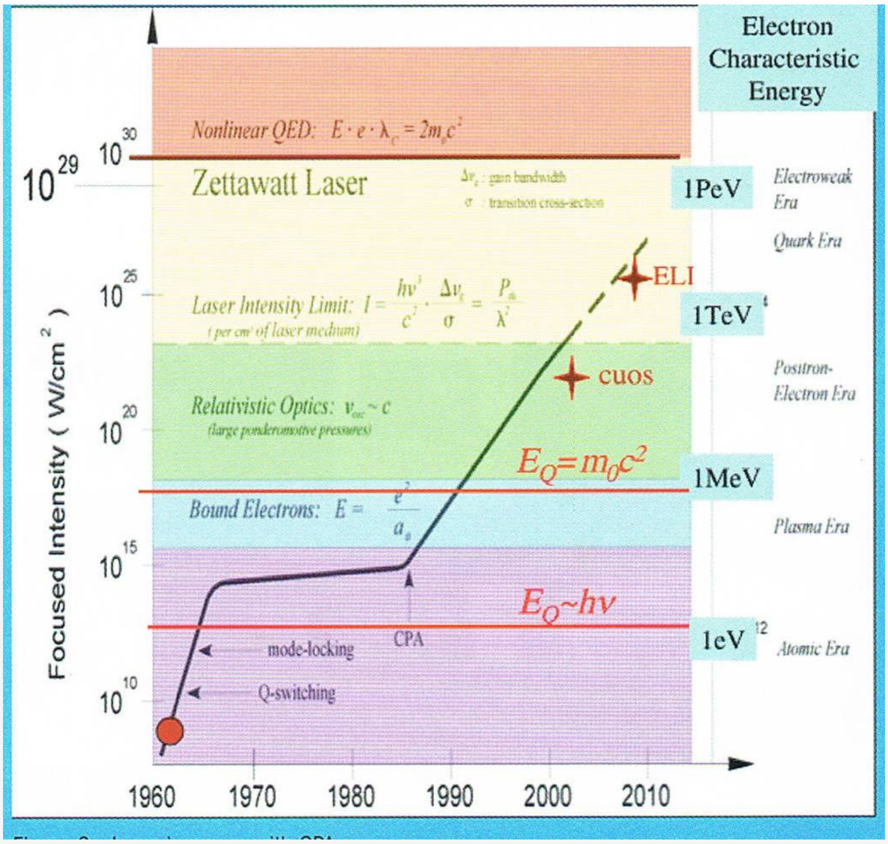

Fig. 6. Development of lasers with the turning point at 1985 with the discovery of the Chirped Pulse Amplification CPA [28].

with nearly no thermal losses is in basic contrast to the spherical nanosecond laser pulse irradiation for very high compression and thermal ignition (CATI) of fuel with the highly developed projects as e.g. NIF [3][4]. CATI is scheduled to work with DT fuel but is about 10^5-times more difficult for the ideal neutron-free hydrogen-boron11 (HB11) reaction as seen from the need with compressions to 100,000 times solid state fuel. This thermal ignition process needs compression of the fuel to 100,000 times solid state density.

It should be noticed that there is another laser-fusion scheme with PW-ps laser pulses based on fast ignition [24] by producing extremely high current density 5 MeV electron beams for ignition of larger quantities of DT compressed to 12times or less of the solid [25]. The generation of the relativistic electron beam by PW-ps laser pulses needs a plasma precompressions with >1000 times solid state density before the extreme intense electron beam ignites the DT fusion fuel. Due to the stopping range of few *millimeters* for the 5 MeV electrons, this DT reaction for power stations needs about 10 PW laser pulses. The ignition of fusion is a thermal volume process and an application to HB11 may again be by orders of magnitudes more difficult similar to the thermal based CATI process and may be impossible. In difference, the non-thermal DICNOF process with the fusion flame with extended plane wave laser interaction within few *micrometer* thickness determined by the dielectric swelling of the skin depth and a similar collective particle stopping, had shown a factor less of 10 of higher difficulties between DT and HB11 [26]. Disadvantages for DICNOF fusion, however, are the lateral losses at cylindrical geometry compared with the Nuckolls-Wood thermal volume ignition scheme [25].

In order to reach the HB11 fusion with the DICNOF scheme, this may be solved with using nanosecond lasting co-axial magnetic fields of few 100 Tesla to suppress the lateral losses [27] such that estimations for a power station may need laser pulses in the range exceeding the 100PW-ps. These laser developments are on the way (Fig. 6), driven by other applications as e.g. for aiming particle acceleration to PeV energies [28] or pair production by vacuum polarization [29].

For the HB11 fusion it was estimated, that the main stopping process of the alpha particles is by electrons [14][26] and much less by ions. This result prevents complications through secondary fusion reactions such that the computations reached up to the present state, have a high probability to cover the real conditions. This can be seen from the following results. At elastic central collisions between the mass m_a of an alpha particle of energy E_a with an initially resting ^{11}B nucleus with the mass m_B, the energy of the boron after collision is

$$E_B = 4m_a m_B E_a/(m_a + m_B)^2$$

Using the initial energy of the alpha partcile from the HB11 reaction of 2.888 MeV, the first elastic hit transferes 2.258 MeV energy to the boron. After this collision, the alpha particle can produce a second hit to boron which is then gaining 492 keV. At a third hit it can transfer 107 keV to a boron.

For the probability of a stopping process of alphas by such an ion collision needs to use the mean free path ℓ of the alphas before being involved in an inelastic collision

$$\ell = 1/(\sigma n)$$

where σ is the cross section and n the ion density. Taking the exceptional high cross section of 1.2 barn cod to 500 keV, the mean free path is 3.44 mm. This is an exceptional low value as a kind of lower bound. The absorption length for the HB11 alphas by electronic interaction within Gabor's collective range is more than 50 times lower for the especially extreme case and normally is much further away from this ratio. This is the reason why stopping of the alphas could be based solely on the electronic interaction.

A further advantage may be to use relativistic driven plasma blocks [21]. For the computations it is important to cover thermal non-equilibrium in details as the Wilks method with the particles in cells PIC permits [30]. Examples of results (see [17]) seem to show no significant differences to macroscopic thermal descriptions. The special conditions of the non-thermal direct conversion of laser energy into motion of plasma blocks may be one way out of the confusing thermal problems of complex systems as studied by Lord May [31] and as envisaged by Edward Teller, expressed in 1952 (see [23] referring to E. Teller, Memoirs p. 344), about the fundamental difficulties for controlled gaining fusion energy based on thermal ignition. The basic non-thermal fusion flame generation by ps and shorter laser pulses should be a way out of these problems for energy generation.

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