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Ultrahigh acceleration of plasma by picosecond terawatt laser pulses for fast ignition of fusion

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Abstract

A fundamental different mechanism dominates laser interaction with picosecond-terawatt pulses in contrast to the thermal-pressure processes with ns pulses. At ps-interaction, the thermal effects are mostly diminished and the nonlinear (ponderomotive) forces convert laser energy instantly with nearly 100% efficiency into the space charge neutral electron cloud, whose motion is determined by the inertia of the attached ion cloud. These facts were realized only by steps in the past and are expressed by the ultrahigh plasma acceleration, which is more than few thousand times higher than observed by any thermokinetic mechanism. The subsequent application for side-on ignition of uncompressed fusion fuel by the ultrahigh accelerated plasma blocks is studied for the first time by using the genuine two-fluid hydrodynamics. Details of the shock-like flame propagation can be evaluated for the transition to ignition conditions at velocities near 2000 km/s for solid deuterium-tritium.

Keywords: Fast ignition; Fusion flame; Laser driven fusion energy; Nonlinear (ponderomotive) force acceleration; Side-on ignition; Uncompressed fusion fuel

INTRODUCTION

Fast ignition for laser driven fusion (Tabak *et al.*, 1994; Campbell 2005) led to a fundamentally new direction in exploring plasma properties at very high laser intensities because of the dominance of nonlinear direct interaction of the laser with the electron cloud in the plasma at picoseconds (ps) and shorter interaction times. This is in drastic contrast to interaction at the nanosecond (ns) scale where complicated thermal processes can dominate. This is best seen from the generated ultrahigh accelerations. Sauerbrey's (1996) discovery of accelerations of 2×10^{18} m/s^2 was based on a convincing measurement by the Doppler shift using comparably modest size lasers. This was more than 2000 times higher than the acceleration with very large scale ns lasers even in 2010 (Karasik *et al.*, 2010). These explorations of acceleration of plasma blocks opened the possibility for a radically modified method of laser driven fusion by fast ignition using the side-on ignition of uncompressed or modestly compressed fuel. The main obstacle of the high acceleration for the Doppler measurement was the presence of relativistic self-focusing (Hora, 1975), which was precluded by using extremely high contrast of the laser pulses to avoid the generation of plasma plumes in front of the target to be irradiated.

Early results on thermal ignition of laser fusion (Yamanaka *et al.*, 1986; Storm, 1986; Storm *et al.*, 1988) suggested that the highest deuterium-tritium (DT) fusion gains can be reached based on shock-free spherical ideal compression. The gains of more than 10^{12} fusion neutrons were significantly higher than all earlier attempts with exploding pushers (Hora *et al.*, 1998) where shocks led to strong degrading deviations from the ideal adiabatic implosion. The ideal adiabatic compression was leading to the highest gains at volume-burn and the discovery of volume-ignition (Hora *et al.*, 1978), confirmed as "Wheeler-modes" (Kirkpatrick *et al.*, 1981), which was then summarized by Hora *et al.* (1998). The discovery of this shock-free adiabatic compression was reached systematically by varying of the experimental parameters and comparing with corresponding computations arriving to the highest gains in contrast to the exploding pusher case, which result was called "Yamanaka compression" (Yamanaka *et al.*, 1986). Gains above 10^{13}

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neutrons were achieved (Azechi *et al.*, 1991) and compression to 2000 times of the solid matter density where it was crucial that laser beam smoothing (Kato *et al.*, 1984) was used (Hora, 2006). Further improvements led to gains up to 2×10^{14} neutrons (Soures *et al.*, 1996) in case of direct drive and volume ignition (Hora *et al.*, 1998).

The greatest problem of these experiments was the rather low maximum temperature T at highest compression (Azechi *et al.*, 1991), which was only about $T = 3 \times 10^6$ K whereas the theoretical expectations for spherical compression and thermal ignition gave significantly higher temperatures. Nevertheless, the spherical compression and thermal ignition scheme was followed up by building the National Ignition facility (NIF) (Campbell, 2005; Moses *et al.*, 2006) leading close to the historic first controlled exothermic nuclear fusion reactions (Glenzer *et al.*, 2011). Simultaneously, with these efforts an alternative was considered by Tabak *et al.* (1994) to overcome the problem of the unexpected low temperature at compressions (Azechi *et al.*, 1991) by "fast ignition." This scheme was based on spherical plasma compression to more than 1000 times solid density and to produce an additional heating of the center area, by a second laser pulse of ps duration with energy in the range above 10^5 J.

This led to the development of picosecond laser pulses with powers above terawatt (TW) to petawatt (PW) using chirped pulse amplification (Strickland & Mourou, 1985; Mourou & Tajima, 2002) for solid state lasers. An alternative method is the use of KrF laser amplifiers for the amplification of ultrashort laser pulses known as the Szatmári-Schäfer method (Szatmári & Schäfer, 1988; Szatmári, 1994).

In this paper, first, we discuss the experimental results concerning the ultrahigh acceleration of plasma blocks using the Doppler effect. After giving the theoretical background of the nonthermal acceleration we consider its application to side-on ignition for laser fusion. Genuine two-fluid hydrodynamic simulations show the achievability of self-sustained fusion with this method for energy flux densities of 10^8 J/cm^2 for DT where intensities of 10^{20} W/cm^2 of KrF lasers are fitting the optimized high densities of the plasma blocks.

SAUERBREY'S EXPERIMENTAL DISCOVERY OF ULTRA-HIGH LASER ACCELERATION OF PLASMA BLOCKS

The observed high Doppler shifts from the expanding plasma fronts (Sauerbrey, 1996) corresponding to accelerations of about 10^{20} cm/s^2 can not be explained any more by thermal pressure processes, which resulted in more than 2000 times lower accelerations beforehand, therefore the involvement of nonlinear electrodynamics came to the front. In the experiments in which KrF laser pulses of about TW power and half picosecond duration were used with the — at that time — most unique condition that laser pre-pulses were cut-off by a factor of 10^8 intensity (contrast ratio) during less than about 10 ps before the arrival of the main pulse onto the target. Planar plasma fronts were generated only in this case where the Doppler shift of the reflected light is a consequence of the ultrahigh acceleration. The difficulty to produce the plane plasma fronts lies in the need of the very high contrast, otherwise amplified spontaneous emission of the KrF laser amplifier results in preplasmas and thus in confusing, non-reproducible results.

A reproduction of the ultrahigh acceleration was possible due to the further improved contrast of the laser pulses by one more order of magnitude, i.e., to 10^9 and re-designing of the laser pulses based on the Szatmari-Schäfer method (Földes *et al.*, 2000; Veres *et al.*, 2004). This improvement resulted in similarly high acceleration even at significantly lower laser intensities as shown in Figure 1, which illustrates the plasma block velocities from Doppler measurement. In these experiments the pulse duration of the KrF laser was $t = 700$ fs with a maximum energy of 15 mJ. The laser pulse of 2.6×10^{15} W/cm^2 intensity resulted in a velocity of $\mathrm{v} = 1.25 \times 10^7$ cm/s of the plasma at irradiation of aluminum (Földes *et al.*, 2000) leading to an acceleration during the short time $t = 700$ fs of

$$a = v/t = 1.6 \times 10^{19}\ \mathrm{cm/s^2}. \tag{1}$$

The question is then, how fast the laser energy can be converted into this plasma motion. This re-evaluation of the experiment is a special point of attention for the following consequences. At this intensity, the quiver energy of electrons is

$$\varepsilon_{osc} = e^2 \boldsymbol{E}_v^2/(2 m_e \omega^2). \tag{2}$$

Here m_e is the electron mass and $\boldsymbol{E}_v$ is the electric field amplitude of the laser of frequency ω in vacuum. This quiver energy of 32 eV is sufficient to produce plasma electrons in the target within several laser periods by the electrons

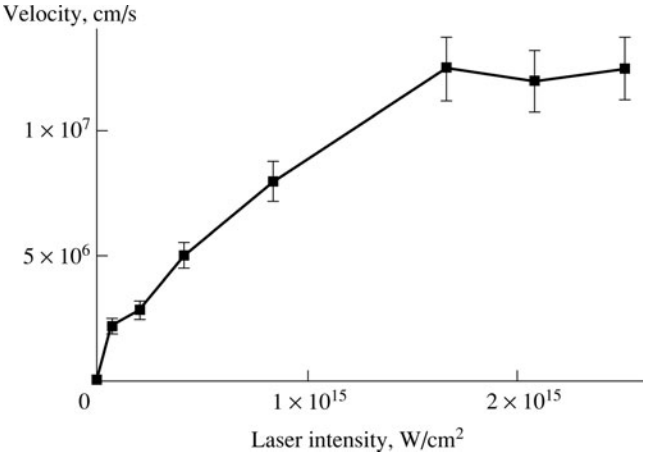

Fig. 1. Intensity dependence of the velocity of the plasma front from the Doppler shift of the reflected 700 fs KrF laser pulses from Al target (Földes *et al.*, 2000).

impacting in the target and with other aluminum ions to be ionized.

The question is what happens after the 700 fs duration of the laser pulse. Any quivering of the electrons caused by direct interaction with the laser electric field has gone. Some thermalization of the quiver energy by collisions of the quivering electrons could have been converted into some electron temperature, as the Gitomer process for fast ion generation (Hora, 2003). The thermalization process from quiver energy into ion energy requires a long time as compared with the 700 fs duration of the laser pulse. Any plasma motion is determined by the directed macroscopic motion of the ions whose front was seen from Doppler shift. It is evident that the measured high energy for the high velocity macroscopic motion of the ions could never have been transferred via thermalization within the 700 fs duration of the direct interaction with the laser pulse.

UNIQUE CONDITIONS OF NONTHERMAL ACCELERATION

The PW-TW laser interaction with targets opened a basic new field of physics, which is mostly related to clarify the mix-up between temporally delayed thermal gas-dynamics against instantly acting direct electrodynamic mechanisms. The fundamental problems were realized by Edward Teller in 1952 (Hora, 2011) by considering the time delayed mechanisms for controlled nuclear fusion reactions, for energy production in view of the then formulated new theory of complex systems (Teller, 2001). This is in connection with the stabilization of complex systems studied by Lord May (1972) and the recent applications (Haldrane *et al.*, 2011). Teller underlined the advantage to use very fast processes to overcome the well-known instabilities etc. This may be the reason why temperature determined ns laser-fusion (Glenzer *et al.*, 2011) is fundamentally different as compared with the electrodynamically determined picosecond case (Hora, 2009; Hora *et al.*, 2010).

Gaillard *et al.* (2011) analyzed their most detailed measurements and summarized the confusing difficulties of explanations with the high-power ps pulses. She — similarly to Sauerbrey (1996) — realized the importance of electrodynamic mechanisms versus thermokinetic ones. Any previous considerations containing only processes in thermal categories failed when taking the measured extremely low energies of the hot electrons (Teubner *et al.*, 1996). These low energies can be explained immediately by the collisions of the quivering electrons during the electrodynamic interaction processes (Hora, 2003). The same consideration applies also to the measurement of the 62 MeV proton emission independently of the irradiated substance (Gaillard *et al.*, 2011) with an intensity $I = 6 \times 10^{20}$ W/cm^2 of neodymium glass laser pulses with very high contrast ratio (Yang *et al.*, 2011). Taking the kinetic energy part of the electron quiver energy in the vacuum laser field of $I/(2cn_{ec})$ with the critical electron density n_{ec}, the value is about 62 MeV. This suggests that the nonlinear force on the electron cloud without swelling in the outermost interaction range has dragged out the proton cloud and then the process of converting the kinetic energy part of the quiver energy into translative proton motion takes place in the same way as known from the radial emission of electrons from a laser beam (Boreham & Hora, 1978; Meyerhofer *et al.*, 1996).

In the outermost range, the conditions are rather simplified without swelling (Hora, 1981). For the following heavier ion groups linearly separated on the charge number Z, the swelling is dynamically changing temporally and spatially, such that any analysis will be more complicated even if thermalization effects are of minor influence as seen from the general numerical analysis (Hora *et al.*, 2007; Sadighi-Bonabi *et al.*, 2010). These hydrodynamic studies are indeed to be supported by particle in cell (PIC) computations where agreement with hydrodynamics at the relevant laser intensities was proved (Klimo & Limpouch, 2006; Hora, 2009). Nevertheless, problems in the PIC simulation arise due to the varying dielectric properties of the plasma given by the dynamically varying optical constants in space and time (Badziak *et al.*, 2005; Sadighi-Bonabi *et al.*, 2010).

The dominating electrodynamic processes in contrast to the thermokinetic ones at ns laser pulses are well described as “direct laser-light-pressure acceleration” (Gaillard *et al.*, 2011), while “nonlinear (ponderomotive) forces” does not specifically characterize the detailed properties. For the latter expression, it is to remind that the forces for instantly acting on the space charge neutral electron cloud by the laser radiation are determined by the descriptions, which are given always by square expressions (Chen, 1974) of fields including electric currents which are linearly related to fields by Ohm’s law. The difference of the nonlinear to the linear definition of forces is given from the linear relation by Coulomb’s law.

In order to understand the measured ultra-high acceleration of plasma blocks by lasers, it has to be recalled that a basically nonthermal interaction process is responsible for it. The final result in hydrodynamic plasma theory is based on the force density $\boldsymbol{f}$ in plasma to be determined by the gas-dynamical pressure $p = n_p kT$ where n_p is the particle density, k is the Boltzmann’s constant and T is the temperature and by the present electric and magnetic fields $\boldsymbol{E}$ and $\boldsymbol{H}$:

$$\boldsymbol{f} = -\nabla p + \boldsymbol{f}_{NL}. \tag{3}$$

The nonlinear force $\boldsymbol{f_{NL}}$ is reduced from the general formulation (Hora, 1969, 1985; Hora, 1991, see Eqs. (8.87) and (8.88)) for a one dimensional geometry of a plane laser pulse interacting with a plane plasma to

$$\begin{aligned} \boldsymbol{f}_{NL} &= -(\partial/\partial \boldsymbol{x})(\boldsymbol{E}^2 + \boldsymbol{H}^2)/(8\pi) \\ &= -(\omega_p/\omega)^2(\partial/\partial \boldsymbol{x})(E_v^2/\boldsymbol{n})/(16\pi), \end{aligned} \tag{4}$$

where E_v is the amplitude of the electric field $\boldsymbol{E}$ of the laser in vacuum. The second expression corresponds to the formulation of the ponderomotive force in electrostatics, while the first expression includes identities from the later Maxwellian theory with the magnetic field $\boldsymbol{H}$ as shown before (Hora, 1991). If the quiver energy of the electrons in the laser field is larger than the energy of the thermal motion, then the nonlinear force is dominating over the gas dynamic force (also called the thermokinetic force $\boldsymbol{f}_{th} = -\nabla p$) in Eq. (3) if the quiver energy of the electrons in the laser field is larger than the energy of thermal motion.

The result of the nonlinear force on the acceleration of plasma could be seen from a plane geometry computations carried out in 1978 for a $10^{18}\mathrm{W/cm}^2$, 1.5 ps duration laser pulse interaction with low reflectivity deuterium plasma after 1.5 ps (Hora, 1981, see Figs. 10.18a and 10.18b). Within these 1.5 ps, a plasma block of more than 18 vacuum wavelengths thickness was accelerated to a velocity of 10^9 cm/s. This acceleration of more than 10^{20} cm/s^2 is comparable with the experimental results of Sauerbrey (1996) and with those of Földes *et al.* (2000) as well as with a more detailed analysis with the experimental conditions showing a very close agreement with the nonlinear force theory (Hora *et al.*, 2007).

The crucial significance of this ultrahigh acceleration for the whole field of laser-plasma interaction — as first measured by Sauerbrey (1996) — cannot be more underlined after it has now been clarified by the ps laser pulses of more than about TW power with the extremely high contrast. This clarification was possible only after nearly 50 years to understand how to distinguish and to eliminate thermal effects. This began with Linlor's (1963) very unexpected measurement of keV ions (instead of classical few eV ions) and the slowly recognition of the nonthermal, instant and direct electrodynamic conversion of optical energy into plasma motion due to the nonlinear (ponderomotive) force though these mechanisms which were partially known as radiation pressure or Lorentz force or electrostriction etc. even before Maxwell's theory. This resulted in the electrodynamic particle acceleration based on the nonlinear theory and was valid also for space neutral plasma blocks with inclusion of dielectric plasma properties (Hora, 1969).

It should be mentioned that the ultrahigh acceleration of plasma blocks was resulted not only from preceding computations by nonlinear (ponderomotive) forces (Hora, 1981) but also from very similar experiments (Kalashnikov *et al.*, 1994) before those of Sauerbrey (1996), well indicating the need of "clean" laser pulses with very high contrast and indicating both thermal and nonlinear force effects. The clarified Doppler shift resulting in the ultrahigh acceleration was achieved by Sauerbrey. The relation with suppression of relativistic self-focusing was shown after the experiments of Zhang *et al.* (1998) and Badziak *et al.* (1999) by theoretical conclusion (Hora *et al.*, 2002*a*, 2002*b*) confirming the connection with the measurements of ultrahigh acceleration (Hora, 2004; Hora *et al.*, 2007).

APPLICATION TO SIDE-ON IGNITION FOR LASER FUSION

After it has been confirmed that the ultrahigh acceleration of plasma is possible with up to solid state density in directed way moving with ion energies in the range of 100 keV within space charge neutral blocks, it was concluded that ion current densities exceeding 10^{11} Amps/cm^2 can be reached (Hora *et al.*, 2002*a*, 2002b). This permitted the application of the side-on ignition of uncompressed solid fusion fuel by very high energy flux density irradiation with ps pulses (Chu, 1972; Bobin, 1974). An updating of the computations of Chu (1972) was performed after inclusion of plasma effects as the inhibition factor and Gabor's collective stopping power which effects were not known at the time of the initial publication. The results were summarized (Hora *et al.*, 2007; Hora, 2009) showing a reduction of the thresholds E* of the necessary energy flux of a few ps irradiation for generation of the fusion flame by a factor up to 20 (Hora *et al.*, 2008) for the ignition of a solid DT target, giving

$$E^* = 2 \times 10^7\ \mathrm{J/cm}^2. \tag{5}$$

A consequence is that laser pulses with very high contrast ratio of more than dozens of PW power and about ps duration should result in very high gain energy production for power stations (Hora, 2009; Hora *et al.*, 2009*a*, 2010).

These computations were performed with single-fluid hydrodynamic models. More details about this ignition process can be obtained by a two-fluid hydrodynamics model (Lalousis *et al.*, 1983; Hora *et al.*, 1984) with separate treatment of the electron fluid and the ion fluid in order to evaluate the electric fields during the plasma dynamics, which can be very large in the highly inhomogeneous particle distributions. In order to be different to other "two-fluid" models where the electric fields are eliminated by averaging processes (Schlüter, 1950), the model is called "genuine two-fluid model," which was first developed with inclusion of general plasma properties by Lalousis *et al.* (1983) and applied for evaluation of double layer effects (Hora *et al.*, 1984; Eliezer & Hora, 1989). Computations up to times of 300 ps after the impact of the ps laser pulse for the ignition have resulted in the development of the fusion flame front moving into the low temperature solid state density DT (Hora *et al.*, 2011*c*, see Fig. 5). It was shown (Hora *et al.*, 2011*b*) that the ion density in the flame was growing up to four times the initial fuel density during the first 100 ps propagation. This value fully corresponds to the Rankine-Hugoniot shock wave theory. Related approaches with impact fusion (Kaiser *et al.*, 1966; Murakami *et al.*, 2006) and shock ignition (Betti, 2010; Eliezer & Martinez-Val, 2011) should be mentioned where again models and special assumptions have to be distinguished from the here reported very general computations.

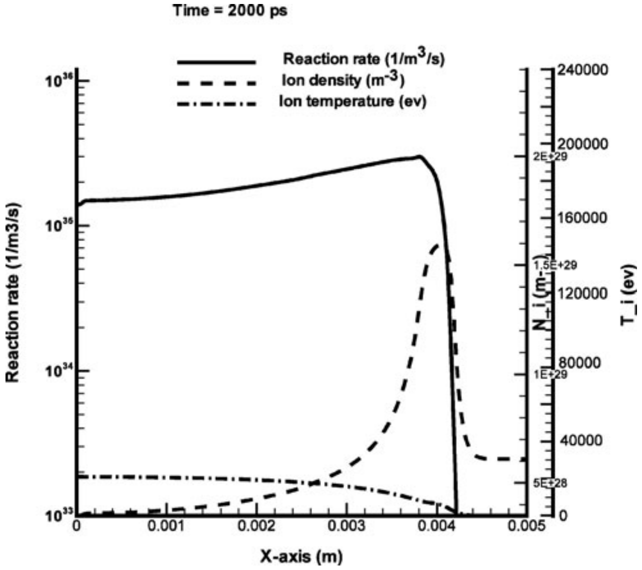

Fig. 2. Genuine two-fluid hydrodynamic computation for the time of 2000ps after a 10^8 J/cm^{2}laser pulse of 1 ps duration irradiated a 5 μm deep surface area of a solid density DT fuel. The reaction rate confirms that the fusion flame has penetrated 4.2 mm into the cold fuel, the flame has a plasma compression shown from the ion density by a factor 1.6.

RESULTS ON THE SPEED OF SELF-SUSTAINED REACTION FRONT

The agreement with the build-up of the shock wave at the reaction front in the low temperature fusion fuel was established only during the early stages of the propagation. This is due to the fact that the analytic shockwave theory is based on a number of simplifying assumptions (steady state), while the computations cover the detailed plasma properties and the effects of the generated alpha particles. In order to follow up to the entire ignition process, computations were carried out for longer times including the reaction rates and evaluations of the velocity of the fusion flame together with the alpha particle production and transport. These computations used laser pulses of 248 nm wavelengths where higher critical densities permit higher laser intensities if one restricts to ion energies in the block to 80 keV for optimizing DT fusion at the resonance of the cross sections.

Figures 2 to 4 report the results for 2000 ps, 1000 ps, and 400 ps, respectively, after initiation of the fusion flame by a 1 ps laser pulse of 10^{20} W/cm^2. The growth of the reaction rate confirms that ignition was achieved for the self-sustained reaction. The velocity of the reaction front during this period is 2014 km/s documenting the success of ignition.

For showing the difference to Figures 2 to 4, Figures 5 and 6 show the result of a similar computation with a laser intensity of only 10^{18} W/cm^2 for the times 2000 ps and 1000 ps, respectively, where no ignition is happening. Indeed, the shock front is generated and fusion reactions from burn without ignition are well appearing but there is no self sustained reaction. The velocity of the shock wave is 320 km/s well confirming that no ignition of fusion was achieved.

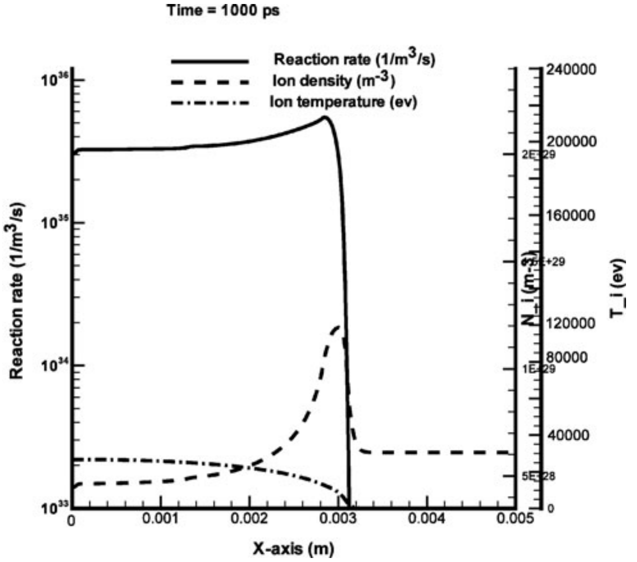

Fig. 3. Same computation as for Figure 2 at the time of 1000 ps.

The evaluation of the velocities of the fusion flame can be used to determine the conditions of the threshold between ignition and no-ignition. Figure 7 summarizes the reaction rates at the time 2000 ps after the 1 ps long block ignition initiated the reactions. The parameter is converted into Joules per square centimetre for comparison of the results using the one-fluid code computations (Hora, 2009). Taking the flame velocity from the depth x onto which the flame has propagated into the solid density DT, Figure 8 summarizes the velocity depending on the energy flux density E^* of the igniting block. A clear change of the line at about $E^* = 10^7$ J/cm^2 is shown in some agreement with the earlier result (Hora, 2009) that there is no ignition

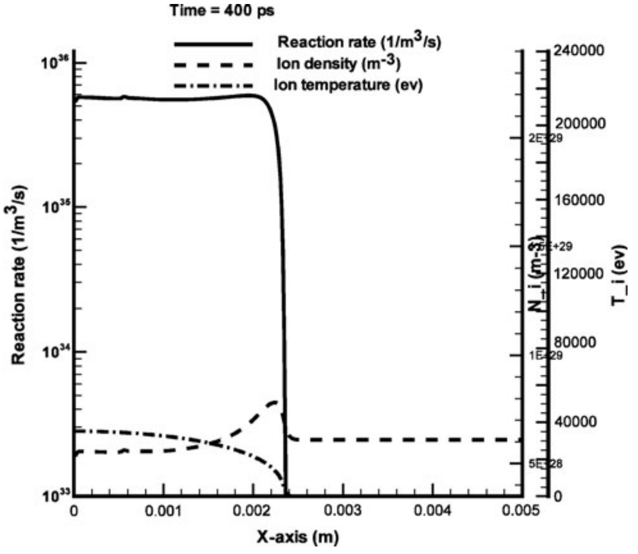

Fig. 4. Same computation as for Figure 2 at the time of 400 ps.

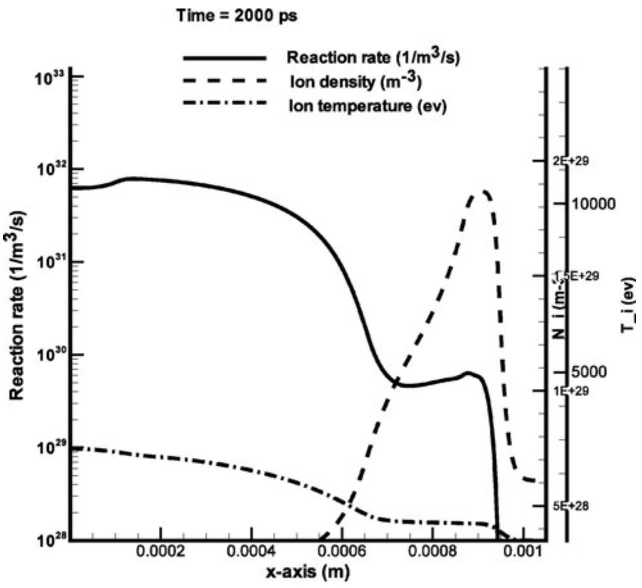

Fig. 5. Same conditions as in Figure 2 but with 100 times lower irradiation intensity at the time of 2000 ps. Ignition is not happening, only decaying reactions. The properties of the shock formation can be followed up.

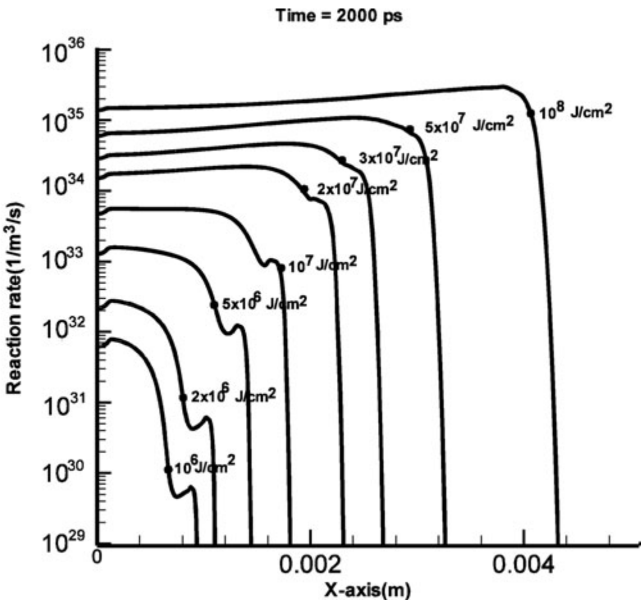

Fig. 7. Summarizing results for the conditions of a sequence of cases as in Figures 2 to 6 for 2000 ps after the block ignition one ps duration. The reaction rates are printed for energy flux densities E^* in J/cm^{2}depending on the depth (x-axis) along which the fusion has gone through the DT fusion fuel of solid density.

below this value of E^* and that this is the beginning toward the condition of ignition. The corresponding velocity 840 km/s is then an important value derived from the here reported computations for igniting a fusion flame in solid DT. The line in Figure 8 for higher velocities above 2300 km/s is definitely in the ignition range and shows a super-velocity of the fusion flame.

At this point, the improvement of the computations by the genuine two-fluid hydrodynamics has to be mentioned, which permits the separation of the temperature of the electrons from the energy of the ions. This was not possible in the model by Chu (1972) and not in the modifications of the improvements of these computations (Hora, 2009). These preceding computations were first approximations for the side-on ignition process while the specifications with the genuine two-fluid hydrodynamics are leading to a more detailed analysis of the processes involved.

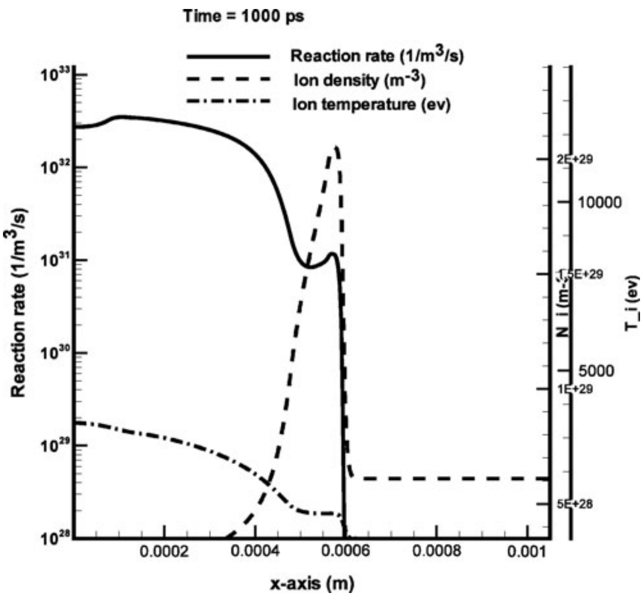

Fig. 6. Same conditions as in Figure 2 but with 100 times lower irradiation intensity at the time of 1000 ps. Ignition is not happening, only decaying reactions. The properties of the shock formation can be followed up.

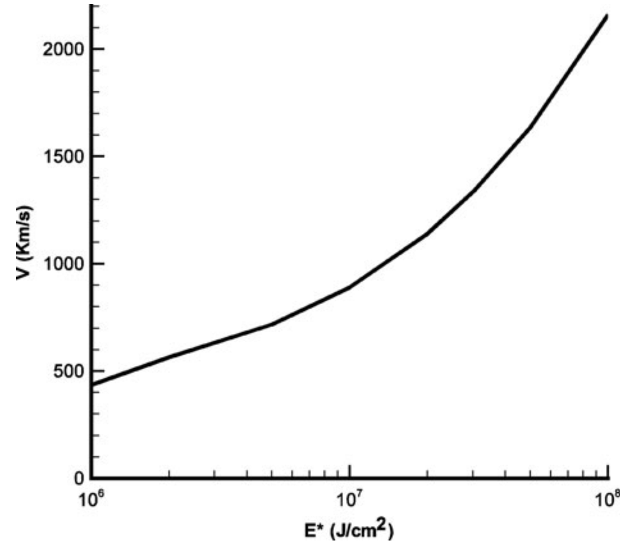

Fig. 8. Velocity v of the fusion flame moving through the solid DT fuel at the time 2000 ps after the one ps block interaction depending on the nonlinear force driven laser flux density E^*as parameter. Showing the beginning of the ignition for E^* values above 10^7 J/cm^2. The transition into ignition is perfect for E^* above 10^8 J/cm^2 with a flame velocity of 2300 km/s.

Comparing Figures 2 to 4 from the ignition case with Figures 5 and 6 without ignition indicates another curious property of the shock process as seen from the ion density. Without ignition, the compression is more pronounced following the direction of the simplified Rankine-Hugoniot theory. The case for ignition with less compression of the flame front indicates that the dynamics of the generated fluid of the alpha particles with the fusion flame in the plasma is changing the conditions much more than the simplified shockwave theory.

DISCUSSION AND CONCLUSIONS

It was experimentally demonstrated that ultrahigh acceleration of plasmas at interaction with sub-picosecond high intensity laser pulses can be obtained if relativistic self focusing (Hora, 1975) is avoided by using very high contrast ratios by suppression of prepulses. The high contrast was necessary with KrF laser pulses to avoid preplasmas generated by ASE and the self-focusing of the ultrashort laser pulse in it. The generation of the ultrafast highly directed planar plasma blocks and avoiding relativistic self-focusing was confirmed also by X-ray emission measurements (Zhang *et al.*, 1998) and the properties of the directed ion blocks based on the fixed number of the fast ions limited to the dielectric strongly increased skin depth (Badziak *et al.*, 1999; Hora *et al.*, 2002*b*). The confirmation of the acceleration by the nonlinear (generalized ponderomotive) force in agreement with computed plane geometry conditions (Hora, 1981; Hora *et al.*, 2007) is demonstrating a non-thermal process where the laser energy was nearly completely converted into macroscopic acceleration of the space-charge neutral electron cloud in the plasma and the electrostatically attached ion cloud. These results are basically confirmed but they may need further information about detailed properties. It was shown that the basic difference between ns and ps interaction is based on the non-thermokinetic properties of picosecond or shorter laser interaction based on instantly working direct electrodynamic interaction by the nonlinear force (Hora, 1969, 1981, 1985, 1991).

The use of the ultrafast plasma blocks for side-on ignition of uncompressed (or modestly compressed) solid fusion fuel following the early computations of Chu (1971) are based on hydrodynamic theory leading to ignition of high gain fusion with next available high contrast laser pulses of dozens of petawatt-picosecond laser pulses for DT fuel and even for HB11 fuel where less radioactivity is generated than from burning coal per gained energy (Hora *et al.*, 2009; 2010).

One problem is whether the hydrodynamic treatment for fusion is sufficient and whether the details of particle interpenetration (Hora, 1983) have to be included as known from PIC computations as discovered by Wilks *et al.* (1991). A comparison between results from hydrodynamics and PIC evaluations for the range of laser intensities of interest (Klimo & Limpouch, 2006) showed a rather good agreement. Nevertheless the study of the complex systems formulated by Edward Teller (2001) with reaching some stabilization criteria by Lord May of Oxford (see references discussed by Hora (2011, 2012)) will be an important access to these problems. Laser interaction with thin foils with high contrast ratio was studied in a number of experiments (see e.g., Kaluza *et al.*, 2004) and may need to be re-considered as in similar cases (Hora, 2003) where the interaction by thermal processes needs a comparison with nonlinear force effects.

These developments were leading to a modification or an alternative to the present fast ignition schemes. Ultrahigh accelerations of plasma by lasers were discovered from direct Doppler measurements by Sauerbrey (1996) which were more than 2,000 times higher than any one known from thermal driven gas dynamic accelerations at laser-plasma interaction. This is a unique new effect, confirmed and reproduced by Földes *et al.* (2000) and Veres *et al.* (2004), in contrast to the broad stream usual thermal acceleration processes. Exactly these measured accelerations were predicted much earlier from the theory of nonlinear effects of laser-plasma interaction which was recognized as a crucial new effect of the laser for non-thermal, instantly acting, and nearly 100% efficient conversion of optical energy into mechanical energy of plasma motion based on computations of 1978 (Hora, 1981).

The results presented here in Figures 2 to 8 lead to the conclusion that the genuine two-fluid computations are confirming the results of previous one fluid computation up to 15 ns (Hora, 2009; Hora *et al.*, 2010, 2011*c*). They confirm the principle of side-on ignition of the fusion flame in solid density DT with ps laser pulses with some additional new details. The ignition could be sustained up to 2 ns after the ps ignition process. Extensions of the very detailed computations, improvements in the organisation of the code are next steps. The present results with inclusion of the electric fields and the separation of the electron and ion fluids with slowly acting thermal exchange permitted the precise evaluation of the flame velocity and the shock process at the flame development with a broadening of the density profiles. This directs the next steps for longer times parallel to the new results about the generation of the alpha particles as a third fluid generation. A remarkable new result is that the velocity of the fusion flame depends on the energy flux density E^* of the initiating ps laser pulse, changing continuously over a rather wide range from the modest slope below the intensity needed for ignition into a steeper slope for ignition. First evaluations based on the present results with the genuine two-fluid computations confirm that high fusion gains will be achieved (Moustaizis *et al.*, 2011).

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