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Application of picosecond terawatt laser pulses for fast ignition of fusion

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Abstract

In this research, we presented the application of picosecond terawatt laser pulses for ultrahigh acceleration of plasma blocks for fast ignition of fusion. Ultrahigh acceleration of plasma blocks after irradiation of picosecond laser pulses of around terawatt power in the range of 10^{20} cm/s^2 was discovered by Sauerbrey (1996) as measured by Doppler effect where the laser intensity was up to about 10^{18} W/cm^2. This is several orders of magnitude higher than acceleration by irradiation based on thermal interaction of lasers has produced. This ultrahigh acceleration resulted from hydrodynamic computations at plane target interaction in 1978 at comparable conditions where the interaction was dominated by the nonlinear (generalized ponderomotive) forces where the laser energy was instantly converted into plasma motion in contrast to slow and delayed thermal collision processes. After clarifying this basic result, the application of the plasma blocks for side-on ignition of solid density or modestly compressed fusion fuel following the theory of Chu (1971) is updated in view of later discovered plasma properties and the ignition of deuterium tritium and of proton-^{11}B appeared possible for a dozen of PW-PS laser pulses if an extremely high contrast ratio avoided relativistic self-focusing. A re-evaluation of more recent experiment confirms the acceleration by the nonlinear force, and the generation of the fusion flame with properties of Rankine-Hugoniot shocks is reported.

Keywords: Fast ignition; Fusion flame; Hydrogen-boron fusion; Laser driven fusion energy; Nonlinear (ponderomotive) force acceleration

1. INTRODUCTION

The research about future options for controlled generation of fusion energy for power stations received an essential turning point by interaction of picosecond laser pulses of powers above terawatts with plasmas resulted in ultrahigh acceleration of plasma layers with a thickness of dielectric increased skin depths (Hora *et al.*, 2002). These plasma blocks contained directed energetic ions with extremely high ion current densities opening a new way of ignition of fusion by direct laser generation of a fusion flame in uncompressed solid fuel (Hora *et al.*, 2007). This reaction as a kind of side-on ignition was considered before as the following described hydrodynamic Chu-model but only the new experimental results of the plasma blocks provided the necessary conditions for a plane geometry interaction for fusion of deuterium-tritium (DT). Fast ignition was the alternative first formulated by Tabak *et al.* (1994) and elaborated (Campbell, 2005) following the discussions about the highest DT fusion gains based on shock-free spherical ideal compression at thermal ignition (Yamanaka *et al.*, 1986; Storm *et al.*, 1986; Storm *et al.*, 1988). 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 led 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) and then summarized (Hora *et al.*, 1998). The discovery of this shock-free compression was reached systematically by varying the experimental parameters in parallel to computations, which, in contrast to those of exploding pushers, arrived at the highest gains as predicted (Hora *et al.*, 1978), the result (Yamanaka *et al.*, 1986) of which was called "Yamanka compression." Gains above 10^{13} neutrons were achieved (Azechi *et al.*, 1991) and as well as compression to 2000 times that of the solid state,

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where it was crucial that laser beam smoothing (Kato *et al.*, 1984) be used (Hora, 2006). Further improvement to gains led to gains of 2×10^{14} neutrons (Soures *et al.*, 1996) all with direct drive and volume ignition (Hora *et al.*, 1998) in contrast to about 1000 times lower gains with indirect drive spark ignition (Lindl, 2005).

What was most disappointing was the rather low maximum temperature T at highest compression (Azechi *et al.*, 1991) of only about $T = 3 \times 10^6$ K, while the theory of spherical compression and thermal ignition said it should have reached higher temperatures. Nevertheless, the spherical compression and thermal ignition scheme was followed up by building the $4 Billion laser facility at the National Ignition facility (NIF) under the initial leadership of Campbell (2006) followed by Moses *et al.* (2006) leading close to the historic first controlled exothermic nuclear fusion reactions (Glenzer *et al.*, 2011), while simultaneously it 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." The scheme at the first discussions (2006) was to use the spherical plasma compression to more than 1000 times the solid state density and to produce an additional heating of the center area by an additional laser pulse of picoseconds duration with energy in the range above 10^5 J. In order to produce laser pulses of this short duration and power above terawatt (TW) and up to more than petawatt (PW), the chirped pulse amplification (CPA) (Strickland *et al.*, 1985; Mourou *et al.*, 2002) was invented for solid state lasers. Another method is the dye laser pulse amplification by KrF lasers known as the Szatmari-Schäfer method (Szatmari *et al.*, 1988; Szatmari, 1994).

These developments were leading to a modification or an alternative to the fast ignition. Ultrahigh accelerations of plasma by lasers were discovered from direct Doppler measurements by Sauerbrey (1996), which were more than 10,000 times higher than any known from thermal driven gas dynamic accelerations from the laser-plasma interaction. This was a unique new effect in contrast to the usual broad stream thermal acceleration processes. In the following, this observation of ultrahigh acceleration is summarized (Section 2). Theses accelerations were measured exactly as predicted from the theory of nonlinear effects of laser-plasma interaction made much earlier. This was recognized as a crucial new effect of the laser for which nearly instant 100% efficient non-thermal conversion of optical energy into mechanical energy of the plasma occurred. In support of the Doppler effects measurements of highly directed plasma blocks by Sauerbrey (1996), Section 3 presents an analysis at subsequent measurements of plasma acceleration with the similar system of sub-picosecond dye laser pulses amplified in inverted excimer plasma (Szatmari *et al.*, 1988; Szatmari, 1994) up to nearly TW laser power. These confirmed plasma blocks of ultrahigh acceleration (Hora *et al.*, 2007) with highly directed and extremely high ion current densities. Section 4 reports the application of these results for igniting solid state density of modestly compressed fusion fuel by side-on laser irradiation for generating a fusion flame following an updating of the scheme of Chu (1971) and Bobin (1974) for DT and for the fusion of proton-^{11}B (HB11). The following discussion in Section 5 focuses on some next questions to be studied.

2. SAUERBREY'S EXPERIMENTAL DISCOVERY OF ULTRA-HIGH LASER ACCELERATION OF PLASMA BY NONLINEAR FORCES

Sauerbrey's (1996) measurement of ultrahigh acceleration of plasma blocks by lasers turned out to be basically a non-thermal interaction process for which clarification was needed and developed in due course, as the problems were of a rather complicated nature. First we give the final short-cut result before going into details. The final result in hydrodynamic plasma theory is based on the force density **f** in a plasma to be determined by the gas-dynamical pressure $p = 3n_p kT/2$ where n_p is particle density, k is Boltzmann's constant and T the temperature, and by the present electric and magnetic fields **E** and **H**.

$$\mathbf{f} = -\nabla_p + \mathbf{f}_{\mathrm{NL}}. \tag{1}$$

For fields of a laser of frequency ω defining a complex optical constant **n** in the plasma, the nonlinear force with the unity tensor **1** is

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

which is dominant over the gas dynamic force (also called the thermo-kinetic force $\mathbf{f}_{\mathrm{th}} = -\nabla p$) if the quiver energy of the electrons in the laser field is larger than the energy of thermal motion (Hora, 1969;1985; see Eqs. (8.87) and (8.88) of Hora (1991)). For simplified one-dimensional geometry and perpendicular laser irradiation, the force (Eq. (2)) can be reduced to the time averaged value (Chen 1974)

$$\mathbf{f}_{\mathrm{NL}} = -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) = -(\omega_p/\omega)^2(\partial/\partial x)(E_v^2/n)/(16\pi), \tag{3}$$

where E_v is the amplitude of the electric field 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 as shown before (Hora, 1991).

Computations for plane geometry interaction with inclusion of the nonlinear force interaction, with thermal laser absorption by collisions, and equi-partition processes in the dynamically developing optical plasma properties for interaction of neodymium glass laser irradiation of 10^{18} $\mathrm{W/cm^2}$ intensity on deuterium having an initial double-Rayleigh density profile (see Hora (1981), Fig. 10.18a and 10.18b), arrived at a velocity distribution and an electromagnetic energy density as shown in Figure 1 after 1.5 ps interaction time. The laser was irradiating from the right-hand side and a plasma block was moving against the laser light and another one into the deeper target. The velocity at this very short time at the closest part to the laser was more than 10^9 cm/s. This corresponds to an average acceleration of more than 5×10^{20} cm/s^2.

These results of the computation were initially published in 1978 (see references Hora, 1981) but it took a long time (Sauerbrey, 1996) before an experimental confirmation of these ultrahigh accelerations were measured. The reason was not only the question how to produce the ps laser pulses up to the range of TW power, but there was the difficulty of relativistic self-focusing (Hora, 1975). Each laser pre-pulse produced a plasma plume where any very intense laser beam which was relativistically squeezed to less than wave length diameter (Fig. 2), producing very high intensities resulting in emission of highly charged ions to energies far above MeV and extremely intense very short wave length X-rays. These extreme mechanisms due to relativistic self-focusing had to be suppressed for verifying the plane geometry of the early computations and also to provide the conditions that the ultrahigh acceleration could be detected directly by Doppler effect.

A confirmation of these conditions in the measurements of Sauerbrey (1996) and the non-thermal processes was supported by following experiments (Zhang *et al.*, 1998; Badziak *et al.*, 1999), after similar measurements led to the conclusion that relativistic self-focusing was suppressed and shown from further related experiments (Hora *et al.*, 2002; 2007; Hora, 2003). This was in drastic contrast to the usual experiments with ps-TW and few PW laser pulses studied by the broad stream of experiments after Cowan *et al.* (1999) observed high acceleration of ions and

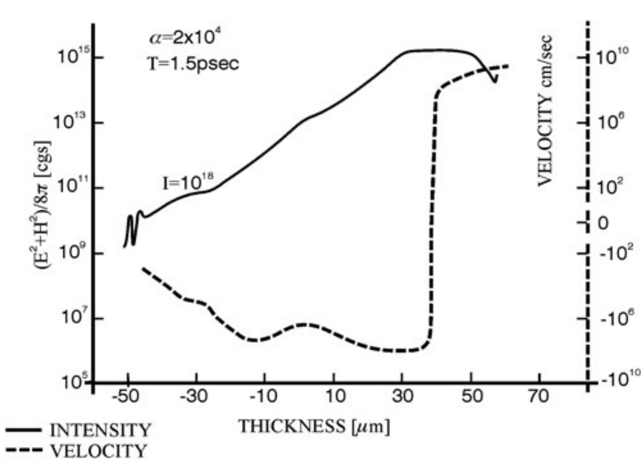

Fig. 1. Hydrodynamic computations in 1978 using 10^{18} W/cm^2 laser irradiation on deuterium close to the critical density resulted in a plasma block moving to the right against the laser light after 1.5 ps showing an acceleration of about 10^{20} cm/s^2 (see Fig. 1 of Hora *et al.*, 2007 from Fig. 10.18a and 10.18b of Hora, 1971).

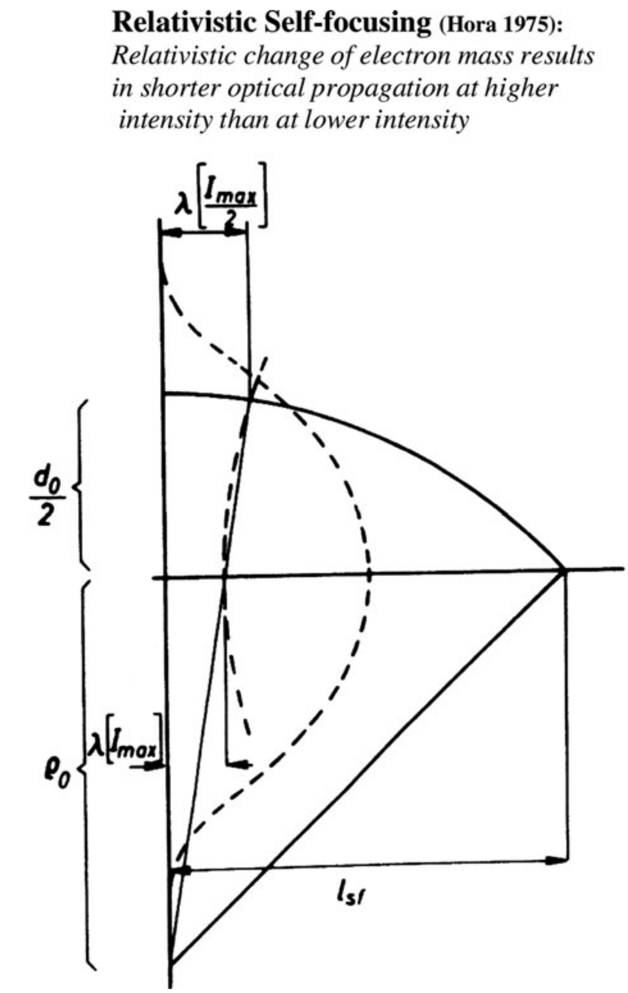

Fig. 2. Relativistic self-focusing of a laser beam from the left with a dashed Gaussian intensity profile and radius $d_0/2$ moves into plasma right from the vertical line. Due to the relativistic change of the electron mass at the quiver motion, the effective wave length within the plasma is dielectrically shorter at higher intensity then at lower causing a concave bending of the initially plane wave front with shrinking of the beam to less than wave length diameter (Hora, 1975; Cicchiteli *et al.*, 1990; Häuser *et al.*, 1992).

electrons, pair production, gamma rays with subsequent nuclear transmutations etc.

The characteristic for the very rare experiments of Sauerbrey (1996), Zhang *et al.* (1998), and Badziak *et al.* (1999), see also Hora *et al.* (2007) is the use of the extremely high contrast ratio above 10^8 for the suppression of the relativistic self-focusing for achieving the enormous suppression of laser pre-pulses before the arrival of the main pulse on the targets. The reason for this was a specific need with the unique KrF laser pulses used by Sauerbrey (1996) where sub-picosecond laser pulses from dye lasers propagated in an inverted KrF laser gas for pulses reaching nearly TW power (Szatmari *et al.*, 1988; Szatmari, 1994). The KrF excimer wave length of 248 nm — in contrast to the longer laser wave lengths of the usually applied lasers – was disturbing the experiments by the amplified spontaneous emission (ASE) radiation where the short wave length was pre-ionizing the

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target too much. It was therefore highly necessary to reduce the ASE to a sufficient degree by suppression of any pre-pulse using plasma mirrors and other techniques for this type of lasers (Szatmari, 1994).

Sauerbrey therefore used lasers with a cut-off of the pre-pulses by a factor above 10^8 (contrast ratio), and had an interaction of the plane one-dimensional wave front of the interacting laser avoiding any self-focusing. The resulting plane wave front geometry provided then for the very first time the conditions for which the interaction was calculated before (Fig. 1). Sauerbrey measured an acceleration of the plane plasma fronts perpendicular to the target of 10^{20} cm/s^2 against the laser as immediately given from the Doppler shift. This was in full agreement with the nonlinear force acceleration as computed before. Variations with respect to experimental accuracy were of minor nature for comparison in view of the significant fact that these ultrahigh accelerations were 100,000 times higher than the thermal pressure acceleration with the largest NIF laser (Park *et al.*, 2010) using nanosecond laser pulses.

3. ANALYSIS OF ACCELERATION MEASUREMENTS WITH DOPPLER EFFECT

Compared with the Doppler experiments with KrF lasers, the continuation with solid state lasers indicated a number of complexities which still have to be studied. It was possible (Yang *et al.*, 2011) that a suppression of relativistic self-focusing for generation of plane plasma blocks as known from the numerous experiments with solid state lasers by Badziak *et al.* (2004; 2005) was possible by the proof of very low emission of X-rays (K. Flippo, private communication, 2011) following the method of Zhang *et al.* (1998). Doppler experiments were performed with KrF ps laser pulses (Földes *et al.*, 2000; 2008; Veres *et al.*, 2004) which are now discussed in view of the later reached clarification between thermal and nonlinear force acceleration processes.

Figure 3 shows the measured plasma block velocities from the Doppler effect at varying KrF laser intensities for 700 fs laser pulses with sufficiently high contrast ratio to suppress the ASE. The laser pulse of 2.6×10^{15} W/cm^2 intensity produced a velocity of 1.25×10^7 cm/s of the plasma at irradiation of aluminium (Földes *et al.*, 2000). This corresponds to an acceleration of 1.6×10^{19} cm/s^2. The question is then, how fast the laser energy can be converted into plasma motion. At this intensity, the quiver energy of electrons

$$\varepsilon_{osc} = e^2 \mathbf{E}_v^2 / (2 m_e \omega^2), \tag{4}$$

using the electron mass m_e is 31.2 eV with the electric field amplitude $\mathbf{E}_v$ of the laser in vacuum for the KrF laser. This is sufficient to produce plasma electrons in the target within about a laser period by the electrons impacting in the target and with other aluminium ions to be ionized. The generation

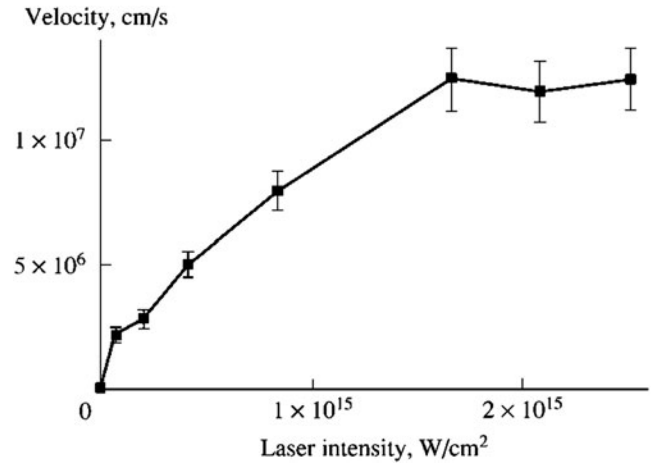

Fig. 3. Intensity dependence of the velocity of the plasma front from the Doppler shift of the reflected 700 fs KrF laser pulses from Al target (Földes *et al.*, 2000).

of an inhomogeneous plasma density in the interaction region can well be assumed to be within this very short time to produce a dielectric swelling $S = 3$ which determines the electric field **E** by dielectric properties given by the temporary and spatially change during the interaction dynamics by the absolute value of the refractive index **n**

$$E^2 = E_v^2/\mathbf{n} \qquad S = 1/\mathbf{n}. \tag{5}$$

This number S can be larger or smaller. The experience from the evaluation of the experiments of Badziak *et al.* (1999) arrived at a swelling of a value of 3 (Hora, 2003). The example of Figure 1 of the numerical velocity of deuterium with an assumed initial Rayleigh density profile had a swelling above $S = 15$. Swelling by $S = 3$ produced a quiver energy of the electrons in the considered case for aluminium within fs duration had an energy of 93 eV and may then have produced high ionization Z of the aluminium. The dynamics of the plasma will then be determined by the nonlinear force (3) acting on the electron cloud again within the time of quiver motion to an acceleration whose dynamics will be determined by the inertia of the ion cloud due to electrostatic attraction in the same way as in the example of Figure 1 in agreement with the experiments of Sauerbrey (1996). Taking full ionization Z = 13, the front of the fastest ions arrives at a velocity of 1.2×10^7 cm/s. In view of a possible higher number S or lower number Z, it is sufficient at this stage only to see that the 700 fs laser interaction is sufficient, to produce the measured acceleration. This is in contrast to any thermal mechanism, where first the quiver energy of the electrons has to be changed by collisions into random motion determining a temperature which then by a rather long equipartition time leads to heat the ions to move with the measured high plasma velocity.

Similar acceleration velocities from Doppler experiments by Veres *et al.* (2004) agree with the considered results from aluminium where the intensity dependence in comparison with the experiments of Badziak *et al.* (1999) and the difference between irradiation of polystyerene and of aluminium may be interpreted along the discussed results of Földes *et al*. (2000). At oblique incidence of lasers on the target, the nonlinear force is directed perpendicular to the plasma surface (see Section 11 of Hora (1991)) and the laser field energy density is not drastically modified.

The acceleration of the ions is happening directly by the conversion of the laser field energy into the nonlinear force driven electron cloud driving the ion cloud by electrostatic attraction. This is in contrast to thermal absorption and heating which takes a much longer time than the interaction of the ps laser pulses. Computations at plasma surfaces with similar initial Rayleigh density profiles as in Figure 1 were performed, however using a later developed genuine two-fluid hydrodynamic computation scheme. This code was developed by using the Euler equations of electrons and for ions separately combined by the electric fields given by the Poisson equation. These internal electric fields in the plasmas were eliminated in Schlüter's (1950) two-fluid hydrodynamics where the Euler equations were added to arrive at a one fluid plasma equation of motion (1) used in the computations of Figure 1, and where the difference of the of the Euler equations led to a generalized Ohm's law for the plasmas. This elimination of the electric fields was correct for homogeneous, uniform plasmas similar to metals where the electric conductivity is similar to plasmas and where any electric field is decaying in much shorter times than fs. For dimensions where the Debye length is much shorter than the considered length dimensions, the electric fields can well be ignored too. If these fields did appear in extraterrestrial plasmas as known by Alfven (1981) and his associates, it was mentioned in a book review about this work by Kulsrud (1983) that "these fields are intuitively not clear."

In contrast to these general views in plasma theory, the genuine two-fluid hydrodynamics showed the strong appearance of these electric fields especially in the highly inhomogeneous plasmas at very intense laser interaction (Lalousis *et al.*, 1983; Hora *et al.*, 1984; see Sections 8.8, 8.9, and 10.7 of Hora (1991)). It was then most interesting to see how these electric fields modify the results of Figure 1. After the genuine two-fluid code was applied to study the experiments of Badziak *et al.* (2005) using genuine two-fluid hydrodynamics (Glowacz *et al.*, 2004; 2006) and other details of the nonlinear force dominating the laser-plasma interaction (Cang *et al.*, 2006), a numerical evaluation was achieved for the initially Rayleigh plasma density profiles similar to Figure 1 (Sadighi *et al.*, 2010), where high swelling factors, *S*, were again the result. It turned out that the net ion motion was not much changed (Fig. 4), compared with Figure 1 due to the fact that there was a dominant non-thermal conversion of laser energy into the macroscopic ion motion by the nonlinear force. The very general code with inclusion of collisions for thermal absorption and equipartition for ion heating were highly delayed and not strongly

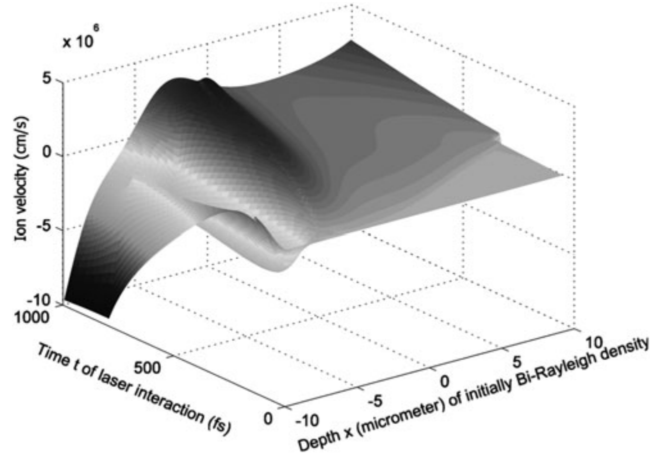

Fig. 4. Ion velocity within an initially bi-Rayleigh $\alpha = 9.59 \times 10^3\ \mathrm{cm}^{-1}$ deuterium plasma with initially zero velocity and with 100 eV initial temperature located between $x = 10$ and $+10\ \mu\mathrm{m}$ at neodymium glass laser irradiation from the left hand side of $2 \times 10^{16}\ \mathrm{W/cm}^2$ intensity during the time between 0 and 750 fs.

affecting the plasma dynamics determined by the ions for the very high laser intensity interactions during pulses in the ps range.

4. APPLICATION TO A RADICAL NEW LASER DRIVEN FUSION OF SOLID DENSITY FUEL WITHOUT NUCLEAR RADIATION

What was important with the ultrahigh acceleration, was that extremely high current densities in the highly directed space charge neutral plasma blocks arrived at $10^{11}\ \mathrm{Amps/cm}^2$ or more. This is again more than a million times higher than accelerators could provide for ion beam fusion and permitted a comeback of the reaction of solid state — uncompressed or modestly compressed — fusion fuel by side-on ignition of a fusion flame. This was absolutely impossible with the first side-on ignition calculations for solid density fusion fuel (Chu, 1971; Bobin, 1974) but this has changed now with the >PW-ps laser pulses (Cowan *et al.*, 1999; Mourou *et al.*, 2002). It is potentially possible for energy production in power stations to achieve gains of 10,000 similar to the Nuckolls *et al.* (2002) scheme using ps-laser produced very high density 5 MeV relativistic electron beams in analogy to the here treated nonlinear force driven plasma blocks based on ions. The theory of Chu (1971) had to be updated (Hora *et al.*, 2008) by the then not known effects of the thermal inhibition factor and by the collective effect of the stopping power (Gabor, 1953).

For laser fusion of DT, extremely clean ps laser pulses with a contrast ratio above 10^8 may drive the controlled reactions in power stations with pulses in the range of few dozens of PW power (Hora, 2009). These are close to technical realization. What was very surprising, is that the reaction of hydrogen and the boron isotope 11 (HB11) is less than 10 times only more difficult than the DT fusion. This will

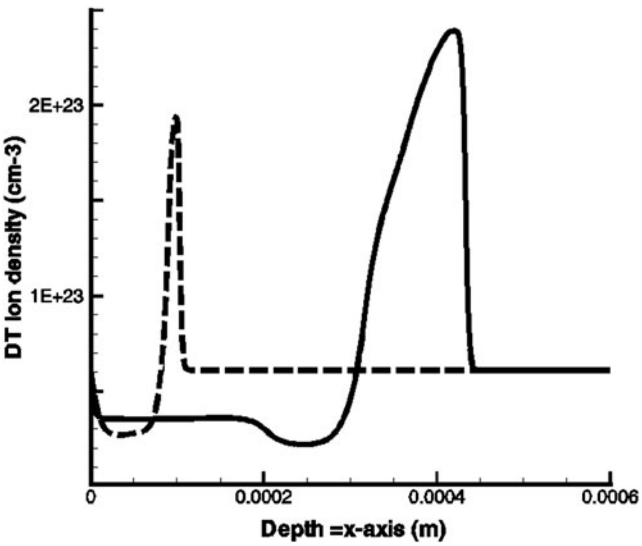

Fig. 5. Genuine two fluid hydrodynamic computations (Lalousis *et al.*, 1983; Hora *et al.*, 1984) of the ion density in solid DT after irradiation of a laser pulse of 10^{20} W/cm^2 of ps duration at the times 22 ps (dashed) and 225ps after the initiation.

generate fewer radioactivities in the entire reaction and in the waste than burning coal, per energy production (Hora *et al.*, 2010; Li, 2010). In contrast to the need of extremely high fuel compression in the usual thermally ignited laser-fusion schemes, the side-on ignition is simplifying the process and it can be expected that power production can be at considerably lower cost than present lowest cost sources, as today's cost in Eurocents/kWh: nuclear fission 2, coal 5, wind 8, photovoltaics 38.

For the next exploration of the side-on ignition of laser fusion with nonlinear force driven plasma blocks, the initial computations (Hora, 2009; Hora *et al.*, 2009; 2010) are now generalized to use the genuine two-fluid model (Lalousis *et al.*, 1983; Hora *et al.*, 1984) in order to study details of shock generation and very high electric field dynamics in the extremely inhomogeneous plasma in the fusion flame fronts. This is also for preparation of specific experiments with PW-ps lasers of sufficient contrast to explore the revolutionary new scheme. Figure 5 shows results of the ion density of the fusion flame when developing into solid density DT fuel after a ps laser pulse initiated the fusion flame. It is very interesting to see that the local ion density in the thin flame front moves with a velocity of 1.55×10^8 cm/s and the density in the flame front is four times higher than the DT. This is an automatic result of the genuine two-fluid computation and agrees with the Rankine-Hugoniot theory of shock generation.

5. DISCUSSION AND CONCLUSIONS

What is evident is the measurement of the ultrahigh acceleration of plasmas at interaction with sub-picosecond high intensity laser pulses if relativistic self-focusing is avoided by using very high contrast ratios for suppression of pre-pulses. The high contrast was initially necessary with KrF laser pulses to avoid ASE. The generation of the ultrafast plane highly directed 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 number of the fast ions limited to the dielectric strongly increased skin depth (Badziak *et al.*, 1999). The confirmation of the acceleration by the nonlinear (generalized ponderomotive) force in agreement with computed plane geometry conditions (Fig. 1) (Hora, 1981; Hora *et al.*, 2007) demonstrated 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 and but may need more information about detailed properties.

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 PW-ps laser pulses for DT fuel but 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 not details of particle interpenetration (Hora 1983) need to be included as known from Particle in Cell (PIC) computations as discovered by Wilks *et al.* (1991). A comparison between results from hydrodynamics and PIC evaluations for the range of interesting laser intensities (Limpouch *et al.*, 2006) showed a rather good agreement. Laser generation at 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 need a comparison with nonlinear force effects.

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