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Review about acceleration of plasma by nonlinear forces from picoseond laser pulses and block generated fusion flame in uncompressed fuel

H. HORA,[1] G.H. MILEY,[2] K. FLIPPO,[3] P. LALOUSIS,[4] R. CASTILLO,[5] X. YANG,[2] B. MALEKYNIA,[6] AND M. GHORANNEVISS[6]

[1]University of New South Wales, Sydney, Australia
[2]University of Illinois, Urbana-Champaign, Illinois
[3]Los Alamos National Laboratory, Los Alamos New Mexico
[4]Institute for Electronic Structure and Lasers IESL/FORTH, Heraklion, Crete, Greece
[5]Campbelltown Branch, University of Western Sydney, Sydney, Australia
[6]Plasma Physics Research Center, I. A. University of Poonak and Coordinated Research Project IAEA Vienna, Austria

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Abstract

In addition to the matured "laser inertial fusion energy" with spherical compression and thermal ignition of deuterium-tritium (DT), a very new alternative for the fast ignition scheme may have now been opened by using side-on block ignition aiming beyond the DT-fusion with igniting the neutron-free reaction of proton-boron-11 (p-^{11}B). Measurements with laser pulses of terawatt power and ps duration led to the discovery of an anomaly of interaction, if the prepulses are cut off by a factor 10^8 (contrast ratio) to avoid relativistic self focusing in agreement with preceding computations. Applying this to petawatt (PW) pulses for Bobin-Chu conditions of side-on ignition of solid fusion fuel results after several improvements in energy gains of 10,000. This is in contrast to the impossible laser-ignition of p-^{11}B by the usual spherical compression and thermal ignition. The side-on ignition is less than ten times only more difficult than for DT ignition. This is essentially based on the instant and direct conversion the optical laser energy by the nonlinear force into extremely high plasma acceleration. Genuine two-fluid hydrodynamic computations for DT are presented showing details how ps laser pulses generate a fusion flame in solid state density with an increase of the density in the thin flame region. Densities four times higher are produced automatically confirming a Rankine-Hugoniot shock wave process with an increasing thickness of the shock up to the nanosecond range and a shock velocity of 1500 km/s which is characteristic for these reactions.

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

1. INTRODUCTION

Catastrophic climatic change by excessive emission of carbon dioxide is evident and expansion of nuclear energy generation is an essential alternative (Hora, 2010). The fact is evident that nuclear energy is about 10 million times more efficient than chemical energy from combustion of fossil fuels. Use of fossils is limited by the amount of carbon dioxide emission to the atmosphere to avoid climatic changes; the problem of nuclear energy is to master the control of generating very dangerous radioactive radiation. Nuclear fission has reached a matured perfect level offering the lowest cost energy production compared with any other large scale energy source despite of its comparably short history of development since its discovery by Hahn and Strassmann (1939) and Miley *et al.* (2010). Fission energy is today the second largest energy generation after burning carbon containing resources. On top, fission energy includes many more options for further reductions of costs and further improvements, e.g., by underground thorium breeders (Teller, 2005; Rubbia, 2010) and small reactors (Guinnessy, 2010) apart from the otherwise reached very high safety levels.

In a not yet sufficient state, is the development to reach fusion energy as energy source in view that all energy production from the sun is of this kind. Enormous expenses

Address correspondence and reprint requests to: Heinrich Hora, Department of Theoretical Physics, University of New South Wales, Sydney, Australia. E-mail: h.hora@unsw.edu.au

for research is well justified because this is promising further options for very dramatic reduction of cost, it is everywhere available, safe and a never exhaustive energy generation in the future. The problem is that at present the sufficiently well known fusion reactions work at very high temperatures while the fission reactors work at or near room temperature. The problem is to confine the reacting fusion plasma where magnetic fields are tried to be used. Despite some technologically achieved success in the past on which further very expensive projects are on the way, this all is insufficiently based on linear physics concepts running in contradicting nonlinear physics results (Hora, 2004). This nonlinear physics was essentially opened (Hora, 1981, 1991) when studying the alternative how lasers or laser driven extremely high energetic particle beams will solve the ignition problem of fusion energy (Hora, 2000, Section 6.3).

The problem with the controlled generation of nuclear fusion was most competently summarized by Edward Teller (2001). He knew from the beginning with his decisions about this research topic for the Lawrence Livermore National Laboratory in 1952 that this is an extremely difficult task because the plasma properties can nearly impossibly be tamed by hydrodynamics for a correct description in physics. This refers not only to the later discovered more or less realized instabilities, but the problem is the entire state of the plasma with its microscopic statistically-uncertain behavior and the long time ignored internal electric fields (Hora, 1991, p. 159) where hydrodynamic description had basic limitations, corrected by the genuine two-fluid hydrodynamics (Lalousis & Hora, 1983; Hora *et al.*, 1984). This is the same with all the attempts to describe the weather by the well known immense hydrodynamic models for predictions. Only when all is going so fast as in uncontrolled nuclear reactions, the times are short enough before the complex processes may develop. A basically new situation was reached by the fast ignition (Tabak *et al.*, 1994) where the timing at ps interaction excludes the mentioned problems with plasmas where the advantage is used by the direct conversion of laser energy into plasma dynamics without the need of thermal processes by the nonlinear force interaction (Hora & Miley, 2005; Hora *et al.*, 2007, 2010; Hora, 2003, 2009) or by laser driven extremely intense relativistic electron beams (Nuckolls & Woods, 2002; Hora *et al.*, 2005, p. 13; Nuckolls, 2010).

In the following, we summarize first for comparison, the present traditional way of laser driven fusion using spherical compression of fusion fuel where the necessary laser has been built with more than megajoule (MJ) energy of nanosecond (ns) pulses (Moses *et al.*, 2006; Moses, 2008, 2010; Glenzer *et al.*, 2010, 2011), for conditions that exothermic reactions of DT may be reached next. Parallel to these ignitions by spherical compression, a fast ignition scheme is under discussion (Tabak *et al.*, 1994), which led to develop of ps laser pulses (Mourou & Tajima, 2001). These laser pulses led to unexpected extreme relativistic interaction effects (Cowan *et al.*, 1999), however, from some few very exceptional experiments led to the discovery of a significant anomaly (Hora *et al.*, 2002*b*, 2007), which could be understood using earlier numerical results about nonlinear force driven block acceleration producing ion current densities of 10^{11} Amp/cm^2, which is about a million times higher than accelerators can reach. This permitted the application of the side-on ignition of solid state density fusion fuel (Chu, 1972; Bobin, 1974). This scheme was impossible to be achieved then, but the conditions of the PW pulses based on the new effect (Hora *et al.*, 2002*b*, 2007) permitted to expect ignition of DT with gains of 10,000 similar to another modification of fast ignition using electron beams (Nuckolls & Woods, 2002). As a surprise, it was possible to conclude the ignition of p-^{11}B at similar conditions as DT in contrast to the spherical compression where exorbitant conditions were needed.

2. TRADITIONAL LASER FUSION WITH SPHERICAL COMPRESSION

The discovery of the laser in 1960 initiated immediately the vision that its extreme concentration of energy in space and time may lead to the solution of producing nuclear fusion energy. Initially, it was evident that fusion energy generation by laser driven ignition needs high compression DT fuel (Nuckolls, 2010). To achieve this, a significant milestone was reached (Moses, 2008) by commissioning of the largest laser in the world, the national ignition facility (NIF), producing laser pulses of more than MJ energy of about nanosecond (ns) duration. Indirect drive by conversion of the laser radiation into X-rays within capsules for smooth fuel irradiation on spheres of DT for heating and compression to more than 1000 times the solid state density n_s is aiming to achieve spark ignition (Lindl, 2005; Glenzer *et al.*, 2010, 2011).

This highly sophisticated process is to reach gains (G) of 50 up to 100 of generated fusion energy per input laser energy producing 10^{19} or more fusion neutrons per shot (Nakai, 2008). The difficulties to achieve conditions of spark ignition (central ignition) are well known and the applied techniques are well developed to achieve this goal. Confidence is given by comparing earlier results (Fig. 1), indicating an increase of the fusion neutrons on nearly the square of the laser energy E_L such that the 10^{12} fusion neutrons with kJ laser energy may reach 10^{18} neutrons at MJ laser pulses.

The confidence to reach such neutron numbers may be estimated also from the alternative compression scheme of volume ignition (Hora & Ray, 1978), which scheme was confirmed (Kirkpatrick & Wheeler, 1981) by evaluation of the "Wheeler modes" and applied with inclusion of self-heating by the generated neutrons (He & Li, 1994; Martinez-Val *et al.*, 1994), and clarified as a rather uncomplicated "robust" method (Lackner *et al.*, 1994). It was rather surprising that the highest measured laser produced yields (Hora *et al.*, 1998, see Fig. 6) were exactly following this volume

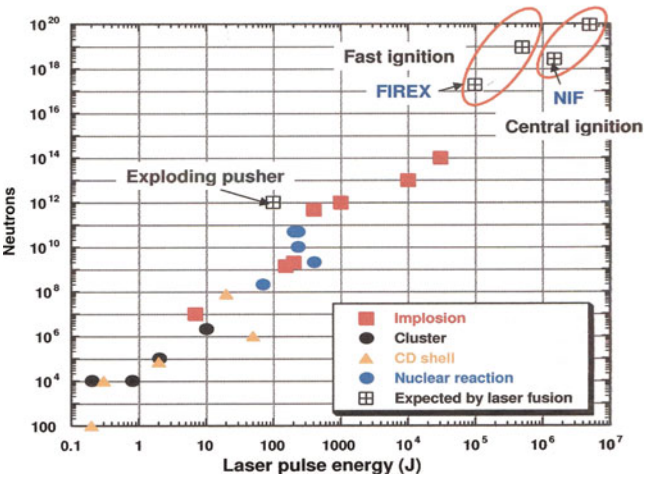

Fig. 1. (Color online) Measured and projected neutron gains at DT fusion using ignition by spherical laser compression depending on the energy of the laser pulse following Nakai (2008).

reaction process (Hora & Ray, 1978), measured in 1985 at Osaka (Yamanaka *et al.*, 1985) and in 1986 at Livermore, and with the ever highest reported values of 2×10^{14} neutrons at Rochester (Soures *et al.*, 1996). From the line shown in Figure 2 (Hora *et al.*, 1998, see Fig. 1) drawn from the experiments. A compression to $1000n_s$ would arrive at 10^{20} neutrons if such linear extension would be permitted. Very probably, the super-linearity for gains $G > 8$ per energy E_0 incorporated into the compressed plasma will produce a faster achievement of the 10^{19} neutrons per shot if the volume ignition (Amendt *et al.*, 2005) will be followed up at the NIF experiments. The line in Figure 2 was drawn in 1991 (Hora, 1991, see Fig. 13.15) before the Rochester results at 1995 (Soures *et al.*, 1996) were known noting the remarkable coincidence of these measurements with the earlier drawn line.

If the verification of the expected reactions using the complex spark ignition (Lindl, 2005) may need a longer time

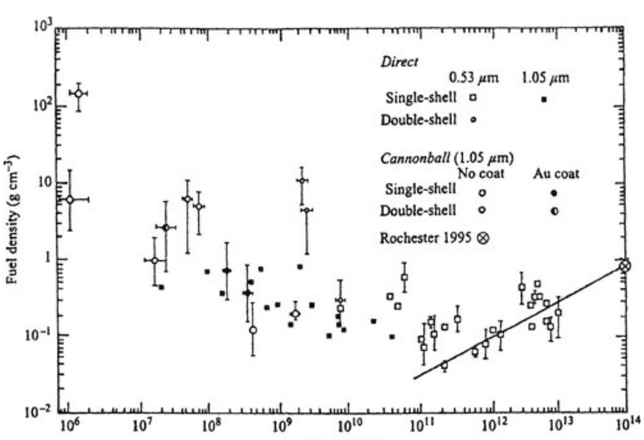

Fig. 2. Measured DT neutron gains from spherical laser compression for direct and indirect drive with single and double shell targets depending on the measured maximum compression, (Hora *et al.*, 1998).

with the experiments, a faster solution for fusion energy may use volume ignition of pellets with ingeniously improvement of (Amendt *et al.*, 2005) double shell compression of targets (see Fig. 2). Even at room temperature this may lead to the gains of 50 or more and to 10^{19} neutrons with NIF. This may at least lead in principle to the conditions for building laser driven inertial fusion energy (Storm *et al.*, 2009; Moses, 2010) as prototype of a fusion power station by 2020 where the solid state laser drivers are diode pumped with more than 15 times higher efficiency for a much more compact laser than NIF. This would be a highly serious and reliable contribution in the fight against the climatic catastrophe using fusion energy.

A reflection may be given to statements by Edward Teller (2001). "Research on controlled fusion means … hydrodynamics of plasmas … for the fearsome nature … where every little volume does its own thing … How fast does each move on the average? What is the electric force … acting on them? The same complications occur in planning a thermonuclear explosion. But an explosion occurs in so short time that many of the complicate phenomena have no chance to develop … It took a decade from Fermi's first suggestions … that the theoretical calculations for thermonuclear explosions were reasonably complete. I had no doubt that demonstrating controlled fusion would even be more difficult."

Our new direction — as mentioned in the Introduction — is that fast ignition (Tabak *et al.*, 1994) has the same advantage to "occur in so short time." On top when getting rid of the delaying thermal processes by instantly working with the nonlinear forces as generalization of ponderomotion for direct conversion of laser energy into motion, this is the new advantage. This is so well documented since Sauerbrey's (1996) measurement of the ultrahigh acceleration after this was long time expected and in full agreement with the theory — confirmed just from hydrodynamics (Hora *et al.*, 1979)! This operation in the picoseconds or shorter range is well guiding, while the large scale laser-fusion experiment in the nanosecond range may just help to explore the open gap of plasma physics formulated by Edward Teller. Simplification may be the key as seen from Figure 1, where the highest measured gains were all with volume ignition and direct drive (Hora *et al.*, 1998; Amendt *et al.*, 2005) to lead to the aimed very high neutron gains with the megajoule lasers. Some relaxation of the difficulties of spherical compression and thermal ignition of HB11 was possible using the latest resonance correction of the fusion cross sections (Kouhi *et al.*, 2011).

3. NEW FAST IGNITION WITH NONLINEAR FORCE

It was necessary for the new developments on laser fusion with ps laser pulses (Tabak *et al.*, 2004) that powers above terawatt (TW) had to be generated. This was achieved by discovering the chirped pulse amplification (Mourou *et al.*, 2002) or the amplification of sub-ps dye laser pulses, e.g., in Schäfer's inverted excimer laser media (Szatmari *et al.*, 1988). The second new aspect is to depart from the usual scheme of laser fusion with spherical compression of fuel pellets in favor of a side-on ignition of modestly (e.g., by chemical explosives) compressed or uncompressed solid density fuel of large volume as the Nuckolls-Wood scheme (Nuckolls *et al.*, 2002) or the Chu-Bobin scheme (Chu, 1972; Bobin, 1974) used in the here presented work (Hora, 2002).

Irradiating (TW to PW)-ps laser pulses (Cowan *et al.*, 1999; Maksimchuk *et al.*, 2000; Ledingham *et al.*, 2002; Kaluza *et al.*, 2004; Flippo *et al.*, 2010) usually results in extreme relativistic effects as generation of highly directed electron beams with more than 100 MeV energy, in highly charged GeV ions, in gamma bursts with subsequent photonuclear reactions and nuclear transmutations (Magill *et al.*, 2003), in positron pair production (Cowan *et al.*, 1999), and high intensity very hard X-ray emission. In contrast to these usual observations, very few different anomalous measurements were reported. What was most important in these few cases, is that the laser pulses with TW and higher power could be prepared in a most exceptional way to have a suppression of pre-pulses by a factor of 10^8 (contrast ratio) or higher for times a few dozens of ps before the main pulse is hitting the target. These very clean laser pulses were most exceptional only and especially possible by using the Schäfer-Szatmari-method (Szatmari *et al.*, 1988) with excimer lasers by Sauerbrey (1996) or with chirped pulse amplification using titanium-sapphire lasers by Zhang *et al.* (1998) and by Badziak *et al.* (1999) using neodymium glass lasers. These exceptional conditions could be understood from the many years earlier derived results of very detailed one-dimensional computations of laser-plasma interaction with dominating nonlinear (ponderomotive) forces (Hora *et al.*, 2002*b*; Hora, 2003). It was shown (Fig. 3) that irradiation of a deuterium plasma block of specially selected initial density (bi-Rayleigh profile) with a neodymium glass laser intensity of 10^{18} W/cm^2 resulted within 1.5 ps in a thick plasma block moving against the laser light with velocities above 10^9 cm/s and another similar block moving with the laser direction into the plasma interior. However, such a generation of plasma blocks was never observed because in all experiments, a minor prepulse produced plasma in front of the target where the laser beam was shrinking to about one wavelength diameter with extremely high intensities due to relativistic or ponderomotive self-focusing (Hora, 1975).

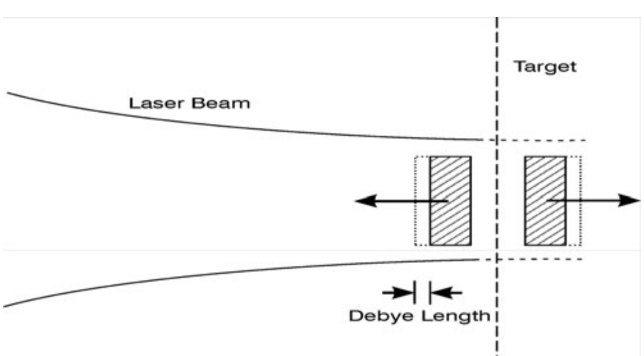

Fig. 3. Nonlinear (ponderomotive) force driven plasma block generation at laser-target interaction (Hora, 2003).

The acceleration was dominated by the nonlinear force f_{NL} given by the time averaged values of the amplitudes of the electric field $\boldsymbol{E}$ and the magnetic field $\boldsymbol{H}$ of the laser in this simplified geometry at perpendicular incidences in the x-direction as (Hora, 1991, 2000)

$$f_{NL} = (\boldsymbol{n}^2 - 1)(\partial/\partial x)(\boldsymbol{E}^2/16\pi) = -(\partial/\partial x)[(\boldsymbol{E}^2 + \boldsymbol{H}^2)/(8\pi)], \quad (1)$$

where $\boldsymbol{n}$ is the complex index of refraction in the plasma. The first expression is the ponderomotive force derived Kelvin for electrostatics before the Maxwellian theory while the second expression represents the force density as gradient of the energy density given in general by the Maxwellian stress tensor. Despite these theoretical predictions since 1981 for picosecond laser pulses of very high intensities (Hora *et al.*, 1979; Hora, 1991, see Fig. 10.18b) it was never possible to measure this process. It was then an important discovery in 1996 thanks to the clean laser pulses of the Schäfer-Szatmari (1988) method, that Sauerbrey measured this process for the very first time. It was essential to use the clean ps laser pulses avoiding the self-focusing (Hora, 1975, 1991, see Section 12.2) and to measure the generated plane plasma block moving against the laser light with an acceleration determined by the Doppler shift. The measured acceleration was very accurately reproduced by the nonlinear force theory (Hora, 1981; Hora *et al.*, 2007) and had a value of

$$a_{NL} = 10^{20}\ \text{cm/s}^2. \quad (2)$$

Such a high acceleration is due to the instant and direct conversion of the electromagnetic energy of the laser pulse into kinetic energy of plasma motion without intermediary heating process where the thermokinetic pressures are generated in much longer times than that of the ps pulse duration. The comparable thermokinetic accelerations using the very extreme conditions of the NIF laser are in the range of

$$a_{th} = 10^{15}\ \text{cm/s}^2 \quad (3)$$

(Park *et al.*, 2010) for use to study acceleration in high energy density astrophysics HEDLA.

It should be noticed that the measurement (Eq. (2)) by Sauerbrey (1996) has a rather large error bar on the order of a factor of two. For the comparison of the experiments with the theory, it has to be taken into account that the dynamically changing dielectric swelling of the energy density in the plasma had to be taken from several other similar experiments, which average value is between 2 and 3 with a similar error bar as the experiment. Apart from this rather complex detail, it is evident that in contrast to thermokinetic pressures with delay times of thermalization and equipartition is significantly larger than ps (Sadighi *et al.*, 2010) than the instantly acting general dielectric modified nonlinear force of the laser radiation on the electrons for acceleration of space charge quasi-neutral plasma blocks.

The second crucial experiment with the discovered anomaly was performed with *clean* laser pulses of about 30 wavelength diameter by Jie Zhang *et al.* (1998) irradiating the target with 300 fs laser pulses. It was very abnormal that there was only a modest X-ray emission, and not the usually very intense hard X-rays. When taking out a weak pulse and pre-irradiate, this at times t^* few ps before the main pulse, the X-rays were unchanged. But as soon as t^* was increased to 70 ps, the usual hard X-rays were observed. It was estimated (Hora *et al.*, 2002*b*, 2007) that the 70 ps were just needed to build up the plasma plume before the target, which is necessary for providing relativistic self-focusing with the subsequent usual very low beam diameter and very high intensities.

A third crucial observation was by Badziak *et al.* (1999) with irradiation of copper targets with half TW very *clean* laser pulses of few ps duration. Instead of the expected and usually measured 22 MeV fast copper ions, the fast ions had only 0.5 MeV energy. Furthermore, it was observed that the number of the fast ions (in difference to the slow thermal ions) was constant when varying the laser power by a factor of 30. From this it could be concluded (Hora *et al.*, 2002*b*, 2007) that the acceleration was from the unchanged volume of the skin layer at the target surface where the nonlinear force produced the generation of a highly directed plane plasma block moving against the laser. This skin layer acceleration by the nonlinear force with avoiding self-focusing was then confirmed experimentally in all details, especially from high directivity of the fast ions and the generation of a plasma block towards the plasma interior, as measured at irradiation of thin foils (Badziak, 2006).

Most significant was the result (Hora *et al.*, 2002*b*) that the generated directed space-charge neutral plasma blocks have an ion current density of

$$j > 10^{11}\ \mathrm{Amps/cm^2}, \tag{4}$$

as it was confirmed experimentally in all details later (Badziak, 2006). The generation of the nonlinear force driven plasma blocks was studied on a broad level (Hora *et al.*, 2002*b*, 2002*a*, 2004; Badziak, 2006; Miley *et al.*, 2006; Hora, 2003; Hora *et al.*, 2007, 2009) where the initially resulting up to 20 vacuum wave length thick plasma blocks (Hora, 1981, Fig. 10.18a and Fig. 10.18b) were re-confirmed numerically (Cang *et al.*, 2005; Hora *et al.*, 2007; Sadighi *et al.*, 2010).

4. COMEBACK OF THE FUSION FLAME USED FOR A RADICAL NEW LASER SCHEME BY SIDE-ON IGNITON

Ion current densities, Eq. (4), of directed DT ions of about 100 keV in the space charge neutral plasma blocks are million times higher than accelerators can produce. This led to reconsidering the Chu (1972)-Bobin (1974) scheme of side-on direct ignition of solid state or modestly compressed DT by the plasma blocks (Hora, 2002) for fusion energy production similar to the Nuckolls-Wood scheme (Nuckolls *et al.*, 2002) using very intense 5 MeV electron beams generated by 10 PW-ps laser pulses. The only difficulty for igniting solid-state density DT is that there is the need of an exorbitantly high energy flux density E^*

$$E^* > 4 \times 10^8\ \mathrm{J/cm^2} \tag{5}$$

derived by Chu (1972) and confirmed by Bobin (1974). This enormous high threshold Eq. (5) seemed to be prohibitive for laser fusion and the classical way of spherical laser compression was followed up (Moses *et al.*, 2008; Moses, 2008). At the new measurements by Badziak *et al.* (1999), values of E^* were well reaching nearly $10^6\ \mathrm{J/cm^2}$. However, the need to generate wide spread, high contrast ratio laser pulses for the highly directed ps ion blocks for side on ignition, only the now available PW pulses will be interesting after the TW pulses at least could demonstrate the basically new conditions for the side-on ignition.

It was then necessary to reproduce the hydrodynamic computations of Chu (1972) and to improve them in view of later discovered phenomena. One of these phenomena is the strong reduction of thermal conduction in laser produced plasmas. This was first observed indirectly from fitting experimental values at laser fusion and led to an empirical inhibition factor which for DT is 69 for the decrease of thermal transport. This reduction could directly be explained by electric double layers (Hora, 1991, 2000, 2009) due to the strong inhomogeneous plasma structures. Another phenomenon for adding to the studies of Chu (1972) was to use the reduced stopping lengths based on the collective effect following Gabor (1952) at the high plasma densities for the generated alpha particles. Without these two additions, the same results of Chu were received (Ghoranneviss *et al.*, 2008) as seen from the temperature T of the detonation front on time t which characteristics depend on E^* as parameter. For reasons of comparison E^* was given in $\mathrm{erg/cm^2}$. An example where both added phenomena were included is shown in Figure 4. When the characteristic were decaying for long time t, no ignition happened. If not decaying, ignition occurred and the threshold $E_t{}^*$ had to be determined. Without the additions, the value of

$$E_t{}^* = 4.8 \times 10^8\ \mathrm{J/cm^2} \tag{6}$$

$$T_{ign} = 7.3\ \mathrm{keV} \quad \text{for DT} \tag{7}$$

resulted in agreement with the results of Chu (1972, see Fig. 2). With inclusion of the inhibition factor and the collective effect (Fig. 4) the threshold was reduced to

$$E_t{}^* = 2.4 \times 10^7\ \mathrm{J/cm^2} \quad \text{for DT} \tag{8}$$

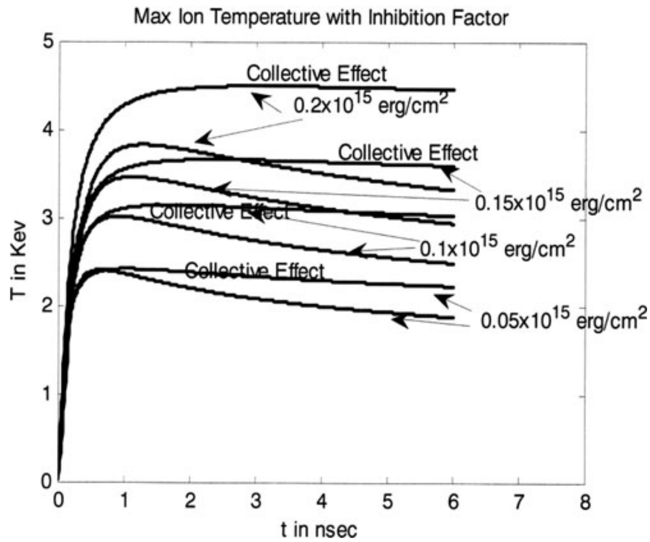

Fig. 4. Dependence of DT plasma temperature T on time t with collective effect and inhibition factor for varying parameter of input energy flux density E^*compared with the decaying curves with inhibition factor only.

with an uncertainty of estimated 50% (Hora *et al.*, 2008). It was estimated that ps laser pulses with more than 10^8 contrast ratio and about 10 to 30 PW power should ignite solid state density DT.

5. GENUINE TWO-FLUID COMPUTATIONS FOR SIDE-ON IGNITION

It had been shown in principle how the drastic difference of nonlinear force acceleration of plasma by lasers is in contrast to thermal pressure acceleration and how laser pulses of ps duration may ignite a fusion flame in uncompressed solid density nuclear fusion fuel if the pulses have a power in the range of PW to exawatt (EW). In order to study the details of the fusion flame generation, one has to apply instead of the one-fluid plasma hydrodynamics of Chu (1972) and the following here mentioned studies, to apply the genuine two fluid model (Lalousis *et al.*, 1983; Hora *et al.*, 1984) in order to evaluate the generated extremely high longitudinal electric fields in the highly inhomogeneous plasma fronts of the flame, and to study its propagation during the interaction with the fuel together with the generation of fusion products. These studies are interesting also for evaluation of shock waves and the shock ignition for fusion (Betti *et al.*, 2007) and impact fusion ignition (Azechi *et al.*, 2009). Studies with advanced PW to EW laser pulses are important also for exotic conditions of shock waves in astrophysics (Park *et al.*, 2011) for experiments on high density laboratory astrophysics HEDLA with ultrahigh accelerations and for related interactions including nuclear mechanisms. It should be mentioned that the genuine two-fluid plasma hydrodynamics (Lalousis *et al.*, 1983; Hora *et al.*, 1984) was well used for studying the block acceleration (Glowacz *et al.*, 2004; Badziak *et al.*, 2004) and optical plasma properties (Cang *et al.*, 2005; Sadighi *et al.*, 2010), but only the following described first results led to the general evaluation of the processes involved. What was important with the ultrahigh acceleration, was that the directed space charge neutral plasma blocks arrived at 10^{11} Amps/cm^2 or more ion current densities. This is again more than a million times higher than accelerators could provide for ion beam fusion, and permitted a comeback of the ignition of solid state — uncompressed or modestly compressed — fusion fuel by side-on ignition of a fusion flame. Following the initial computations of Chu (1972), this seemed to be completely impossible but this has changed now with the greater-than PW-ps laser pulses. It is potentially possible for energy production in power stations to achieve gains of 10,000 similar to the Nuckolls-Wood scheme (Nuckolls *et al.*, 2002) using ps-laser produced very high density relativistic electron beams instead of the here treated nonlinear force driven plasma blocks.

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 a few dozens of PW power. These are close to technical realization. Avoiding 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 low cost.

The updated computations of Chu (1972) were based on one-fluid hydrodynamics (Hora *et al.*, 2008; Hora, 2009) while the genuine two-fluid hydrodynamics (Laousis *et al.*, 1983; Hora *et al.*, 1984) with evaluation of the very high electric fields within the extremely inhomogeneous plasmas were well used to see the dielectric effects at the laser-plasma interaction (Hora *et al.*, 2007; Hora, 2009; Sadighi *et al.*, 2010). We report here about the first extension of the updated Chu (1972) computations by using the genuine two-fluid model including the fusion reactions and the details of the generation of the fusion flame. This is done also for preparation of specific experiments with PW-ps laser of sufficient contrast to explore the revolutionary new scheme (Hora *et al.*, 2010). 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 untouched cold DT. This is an automatic result of the genuine two-fluid computation and agrees with the Rankine-Hugoniot theory of shock generation.

Figure 6 shows the computation for a 2 ps irradiation of 2×10^8 J/cm^2 laser pulse into 5 μm deep surface area of a solid state DT target at the time of 2000 ps after irradiation. The reaction rate shows the successful ignition and the plot of the ion density show the compression to four times the initial solid state fuel in the flame region of about half mm thickness. Behind the flame, the density of the plasma is less than the solid state due to the thermal expansion where the reaction had gone over. From comparing the point of the

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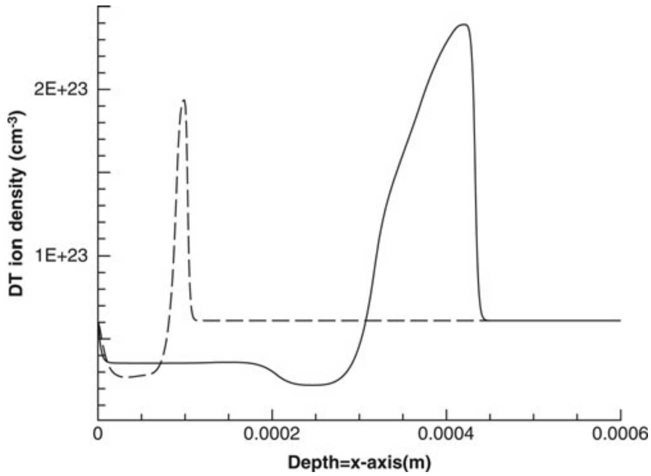

Fig. 5. Genuine two fluid hydrodynamic computations (Lalousis *et al.*, 1983; Hora *et al.*, 1984) of the ion density in solid DT after irradiation of a laser pulse of 10^{20} W/cm^2 of ps duration at the times 22 ps (dashed) and 225 ps after the initiation.

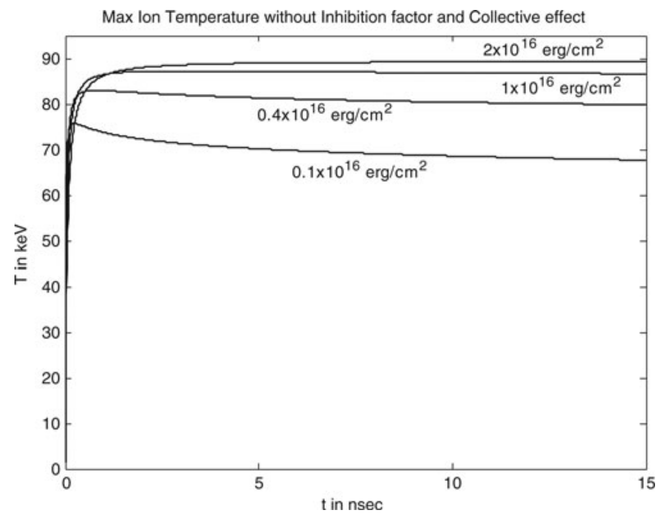

Fig. 7. Characteristics of the kind of Figure 4 for p-^{11}B under the assumptions most similar to Chu (1972) for comparison with DT fusion (Hora *et al.*, 2010).

hit of the flame in the cold fuel at times 1 ns and 2 ns, the propagation velocity of the flame is 1300 km/s at this time. The same computation for a laser irradiation with 2×10^6 J/cm^2 does not show ignition though an initial reaction as a kind of an impact fusion has been shown in the calculations. This case was evaluated for the generally more favorable conditions to use KrF laser pulses (Teubner *et al.*, 1996; Osman *et al.*, 2007; Sadighi-Bonabi *et al.*, 2010), which Sauerbrey (1996) had used for his experimental discovery of the ultrahigh plasma block acceleration.

The shock velocity of around 1400 km/s for later times of the fusion flame shows more and more a deviation of the density profile differing from the simplified shock wave theory. This is evident from the output of the fast velocity of the generated alpha particles when moving into the untouched solid DT by gradually changing there the conditions of densities and temperatures. However, the velocity of the entire flame is nearly unchanged. The genuine two-fluid computations arrive at many more details than known from the one-fluid computation. It is important to note that these studies are aimed to apply ps laser pulses in the range of 30 PW up to nearly EW. Generalizing the preceding computations (Hora, 2009; Hora *et al.*, 2010), the genuine two-fluid hydrodynamics is used in order to follow up the details of the generated very high electric fields in the shock fronts and to confirm some modifications while most of the other results calculated before with the usual one fluid hydrodynamics are rather unchanged. The results are interesting for astrophysical cases and for shock ignition of fusion (Betti *et al.*, 2007) where in contrast to the thermal pressure process used in these computations, the new research now was generalized to non-thermal nonlinear force direct conversion of laser energy into plasma motion to reach the ultra-high accelerations.

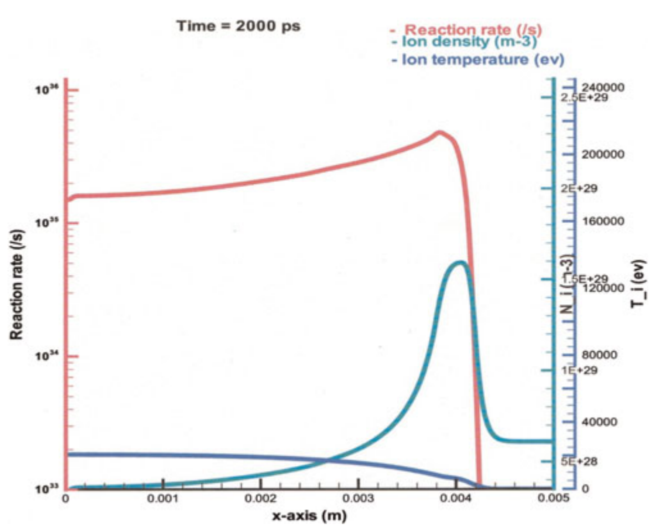

Fig. 6. (Color online) Genuine two-fluid hydrodynamic computation for the time of 2000 ps after a 2×10^8 J/cm^2 laser pulse irradiated a 5 μm deep surface area of a solid density DT fuel. The reaction rate (highest curve) confirms that the fusion flame has penetrated 4.2 mm into the cold fuel; the flame has a plasma compression by a factor 2.6 (second highest line) which is a long time alteration of the Rankine-Hugoniot theory and a thickness of about 1.4 mm, and the curve of the ion temperature.

6. FUSION ENERGY WITHOUT DANGEROUS RADIATION

From the beginning of fusion energy research, a dream reaction is

$$p + {}^{11}B = 3\,{}^{4}He + 8.664\,\text{MeV} \tag{9}$$

because no neutrons are produced and the resulting alpha particles are mono-energetic of 2.888 MeV for irradiating protons with energies up to 200 keV as used in the following. Strong deviations for higher energies were measured only recently in agreement with the Breit-Wigner theory (Stave

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et al., 2009). The result (Eq. (9)) is ideal for high-efficient direct conversion into electricity with minimum heat pollution or after redirecting of the alphas with magnetic fields for space propulsion. Secondary reactions lead to radioactivity but this is less per produced energy than burning coal due to its natural contents of 2 parts per million of uranium (Weaver *et al.*, 1973) and may be considered as negligible. However, it was evident from the beginning that this fusion reaction is very much more difficult than using DT fusion fuel, as seen from the spherical laser compression of p-^{11}B needing densities of 100,000 times the solid state (Hora, 2002) and input laser pulses of several 10MJ energy to produce modest energy gains per laser energy of less than 25 (Scheffel *et al.*, 1997). These conditions are exorbitant and excluded any hope for laser driven p-^{11}B fusion by *spherical* compression. The factor 100,000 is based on the 100 times higher compression than the about 1000 solid density for DT, the necessary 100 times higher input energy of the laser and the 10 times lower gains.

To be consistent with the results of Chu (1972) with DT fuel, computations were first performed based on his assumptions. The p-^{11}B fusion reaction rates given by the reaction cross section σ averaged for a temperature T over a Maxwell distribution of the velocity v of the particles are shown in Figure 6. Using the $<\sigma v>$ -values for p-^{11}B reaction rates instead of DT, results in the time dependence of the plasma temperature T shown here in Figure 6 in analogy to Figure 4 for DT. The parameter of the curves is the energy flux density E^*. What is important is to find the value of $E_t{}^*$ of the ignition threshold where the plasma temperature T merges into a constant value in the dependence on time t. In order to define the threshold $E_t{}^*$ for p-^{11}B, the computation of the temperature T in Figure 6 was going to rather long times (15 ns) in order to see the stationary values. It can only be estimated that the final value is

$$E_0{}^* = (1.5)\times 10^9\ \mathrm{J/cm^2} \pm 30\%, \tag{10}$$

$$T_{ign} = 87\ \mathrm{keV}(\text{p-}^{11}\mathrm{B}). \tag{11}$$

These results seem to be very remarkably modest compared with the values of DT (Eq. ((4)) according to Chu (1972). In view of the exorbitant difference between DT and p-^{11}B for volume ignition based on spherical pellet compression, it is really surprising how much easier the ignition of p-^{11}B works for a side-on generated thermonuclear reaction wave.

The correctness of the shown hydrodynamic results may be seen in the derived proof of consistency shown in the resulting temperatures. In the case of DT, the ignition without reheat and without partial X-ray re-absorption dropped from the (energy averaged value) of about 12 keV for spherical compression to 7.2 keV even under the simplified conditions of Chu (1972) only. There is a clear similarity to the case of p-^{11}B. In this case, the temperature for the spherical compression without reheat and without partial self-absorption is in the range up to about 150 keV (Scheffel *et al.*, 1997), while the here reported side-on ignition of solid fusion fuel arrived at 87 keV temperature for the side-on ignition with the assumptions of Chu (1972) only (Fig. 6 and Eq. (11)). The problem of re-absorption for spherical compression with thermal volume ignition is well including whether the bremsstrahlung is re-absorbed by collisions or additionally by Compton scattering (Meyerhofer *et al.*, 2008). For the volume ignition case, neglecting the Compton process may result in lower fusion gains (Scheffel *et al.*, 1997) only as a lower, pessimistic level of gains. The situation is basically different for the case of the fusion flame at side-on ignition by nonlinear force driven plasma blocks, where the inclusion of bremsstahlung in the code is for a complete energy loss has been well included, but any re-absorption within the thin front of the fusion flame can be neglected.

The basic result of this work is to confirm that side-on ignition of uncompressed p-^{11}B fuel is not very much more difficult than DT fusion and estimated to be possible with laser pulses in the range of ps duration and several dozens of PW power if not some slight pre-compression or the inclusion of other effects will permit a further reduction of these well feasible conditions.

Details of the computations clarified that the radiation losses were sufficiently low for DT and p-^{11}B reactions. Otherwise no ignition at all could have been seen beginning with the plots of Chu (1972) (Fig. 2), and finally for the p-^{11}B reactions. Bremsstrahlung is not nuclear radiation, its nature is x-radiation up to about 100 keV which will not produce nuclear reactions, and may be eliminated by sufficient screening in power stations as known from the usual handling of X-rays.

7. SUMMARY

For the here described modification of fast laser ignition by nonlinear force produced plasma blocks, a much more detailed analysis is needed but at least the basic characteristics for side-on ignition are clearly visible. Most significant are the very surprising results that uncompressed p-^{11}B can be ignited. This fusion energy generation with laser pulses in the range of several dozens of PW power and ps duration can achieve p-^{11}B power production (Hora *et al.*, 2009, 2010). The remarkable fuel avoids neutron generation, results in negligible radioactivity, and allows direct energy conversion, which in turn reduces heat pollution. Such a power plant is ideal for stationary electrical generation in a power station or for space propulsion. Modest pre-compression by chemical driving (Nuckolls *et al.*, 2002) or with high density cluster methods (Holmlid *et al.*, 2009; Yang *et al.*, 2011) could improve the performance even further, especially for p-^{11}B. The X-ray radiation produced in the reaction chamber is ≤ 200 keV which can be screened off and does not lead to nuclear reactions in the power stations (Guyot *et al.*, 1971; Miley, 1970, 1971, 1976, 2005). This provides an exciting vision of a very attractive sustainable future power plant for worldwide use. Its achievement will depend on continued advances in laser optics, target physics and power conversion technology. However, the studies reported here show that such a system is rather close at hand — something not realized before, since p-^{11}B ignition had always been viewed as virtually impossible. This development was in principle favorably acknowledged in an IAEA review by Tanaka (2009). The results of the side-on ignition of p-^{11}B were described in more details (Hora *et al.*, 2010). It was mentioned by Steve Haan, from the National Ignition of Fusion NIF project in an interview by the Editor (Li, 2010) of the Royal Society of Chemistry in London, that the result "has the potential to be the best route to fusion energy."

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