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Collective stopping power in laser driven fusion plasmas for block ignition

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Abstract

In contrast to the usual laser fusion scheme with spherical irradiation and very high compression and ignition of fuel, the alternative scheme with side-on ignition of uncompressed solid density of fuel (Chu) may lead to a solution by using the now available picosecond laser pulses with higher than petawatt power. A necessary condition is to use clean laser pulses with better than 10^8 contrast ratio for suppression of relativistic self-focusing. When updating the analysis of Chu for fusion of deuterium-tritium and proton-^{11}B, one problem is that the correct use of the stopping power of the alpha particles had to be solved. Discrepancies are evaluated in view of the stopping power at the low temperature range of the plasmas where the change of the emitted bremsstrahlung is involved.

Keywords: Collective effects; Inertial fusion; Stopping power

1. INTRODUCTION

The anomaly of laser plasma interaction at laser pulses of terawatt (TW) to more than petawatt (PW) power and picosecond (ps) duration led to a very unique generation of quasi-neutral plasma blocks by a skin layer interaction avoiding the relativistic self-focusing (Hora *et al.*, 2007). The anomalous interaction of ps-PW laser pulses produces highly directed space charge neutral plasma blocks with directed ion current densities above $10^{11}\mathrm{A/cm^2}$ with KeV ion energies due to the action of the nonlinear (ponderomotive) forces. This is in contrast to numerous usual experiments. The plasma blocks may be used for a fast ignition scheme with comparably low compression or solid state density deuterium-tritium (DT) fuel. This side-on ignition laser-fusion scheme is basically different from the usual spherical irradiation scheme with very high plasma compressions far beyond 1000 times the solid state of DT fuel. The alternative side-on ignition had arrived at the difficulty as a very high energy flux density E^* of the laser driven ions is necessary according to the hydrodynamic theory (Chu, 1972).

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The situation has been changed with the appearance of the PW-ps laser pulses to overcome the difficulties with the possibility of the side-on ignition instead of spherical compression (Hora, 2003, 2007; Nuckolls & Wood, 2002; Badziak *et al.*, 2006). A further relaxation of the extreme limitation of conditions for the side-on ignition is possible by a revision of the hydrodynamic analysis of Chu (1972) in view of the later discovered collective effect for the stopping power of the alpha particles and the reduction of the thermal conduction due to the inhibition factor (Ghoranneviss *et al.*, 2008; Hora *et al.*, 2008; Malekynia *et al.*, 2009). One problem appears about the correct use of the stopping power of alpha particles in plasmas at plasma temperatures below keV. At the very high plasma densities, it is evident that the Bethe-Bloch binary collision theory—expressed by the Winterberg formula (see Eq. (7) of Chu, 1972)—cannot be used. Instead the collective collision theory (Gabor, 1952; Ray & Hora, 1977) has to be applied. The inclusion of the collective effect results in a reduction of the threshold value of E^* for ignition by a factor of about five, however due to a discrepancy of the various models about the modified Bethe-Bloch theories (Stapanek, 1981; Gericke, 2002; Deutsch & Popoff, 2007). Results are reported to this question extending the preceding studies

(Malkynia *et al.*, 2009), and the related questions about bremsstrahlung emission will be discussed following the initial inclusion of Chu (1972) in the hydrodynamic analysis.

2. PLASMA BLOCK GENERATION MECHANISM

Problems appeared from the discovery of few rare observations of anomalies at the interaction of laser pulses of TW power and ps duration in contrast to the usually measured relativistic effects. Zhang *et al.* (1998) was applying very clean laser pulses where the prepulses were suppressed by a factor 10^8 (contrast ratio) until 50 ps before the main pulse arrived leading to measured very low X-ray emission in contrast to the usual experiments. Measuring the energy of the fast ions with such clean pulses, Badziak *et al.* (1999) arrived at much lower ion energies than usual and the number of the fast ions did not change by varying the laser power. This led to the explanation that relativistic self-focusing was suppressed and a predominant nonlinear (ponderomotive) force acceleration occurred resulting in directed plasma blocks from the skin layer (Hora *et al.*, 2002, 2007; Hora, 2003).

The resulting plasma blocks with ion current densities above 10^{11} A/cm^2 could then be directly applied to the side-on ignition of uncompressed DT as calculated by Chu (1972) and Bobin (1974) in similar way as a modified fast ignition scheme using 5 MeV intense electron beams (Nuckolls *et al.*, 2002) for ignition of DT at low compression of only about 10 times higher density than the solid state. In both cases, with the ion currents of the blocks or the electrons, the crucial problem of the necessary high thresholds E_t* for the energy flux density E* may be reached as calculated from hydrodynamics (Chu, 1972; Bobin, 1974). This threshold even may be reduced by a factor up to 20 due to interpenetration processes of the particles (Hora, 1983). Another relaxing correction of the threshold E_t* is possible by later discovered effects. One of these phenomena is the stopping power of the alpha particles from the fusion reaction in the target by collective effects. After reviewing the background of the mentioned collective effect, the results of the hydrodynamic theory are reported.

3. EMISSION OF BREMSSTRAHLUNG

The whole analysis of Chu (1972) included the emission of bremsstrahlung from the interaction region at varying the incident energy flux density E* given in J/cm^2 or ergs/cm^2. The key process of the ignition could be seen in diagrams of the generated temperature T in the interaction area depending on time t (see Fig. 2 of Chu (1972)). Ignition was seen when the resulting curves did not decrease. The limiting curve going into constant $T(t)$ for large t defined the threshold E_t* for this side-on ignition. Irradiating solid DT fusion fuel arrived at the value 4.3×10^8 J/cm^2 which was out of any range to ignite solid DT by laser or energetic particle beams. Interestingly, the evaluation of very detailed computations (Storm *et al.*, 1988) of spark ignition for spherical laser fusion (Hora *et al.*, 1998) resulted in similar or one order higher E*-values for generating the detonation front from the central spark produced by volume ignition for moving into the very high density and modest temperature outside fuel mantle.

Since the nonlinear force driven plasma block generation resulted in space charge neutral directed plasma of modest temperatures and directed ion energy up to 100 keV with ion current densities above 10^{11} Amps/cm^2, it became possible to reach the conditions for side-on ignition of uncompressed DT with PW-ps laser pulses. Figure 1 shows the results without inhibition factor (Ghorannevis *et al.*, 2008) with E* as parameter for the ignited cases. The lower set of curves is for the same conditions of Chu (1972), while the higher set refers to the later discussion. The lowest curve shows how T merges into a constant value for high t showing that the threshold for ignition is as known from Chu

$$E_t^* = 4.3 \times 10^8 \mathrm{J/cm^2} \text{ with a plasma temperature of } T_t = 6.9\,\mathrm{keV}. \tag{1}$$

For lower values of E*, the curves decayed on time corresponding to no ignition. The code could be used to compute the total amount of emitted bremsstrahlung per generated fusion energy. This factor was plotted in Figure 2 for decaying curves of input energy flux density. The factor was one for the ignition threshold given in Eq. (1) and then increasing for lower E*.

This factor of unity of Figure 2 could alternatively be used to determine the ignition condition of using the plots of Figure 1 for stationary plasma temperature.

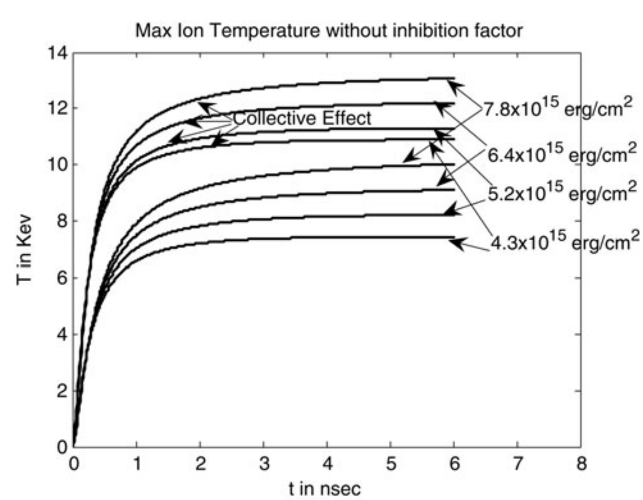

Fig. 1. Side-on ignition characteristics following Chu (1972) for laser ignition of solid state DT by nonlinear force driven plasma blocks. Lower set of curves to reproduce the results of Chu (1972), upper set with later discussed collective effect.

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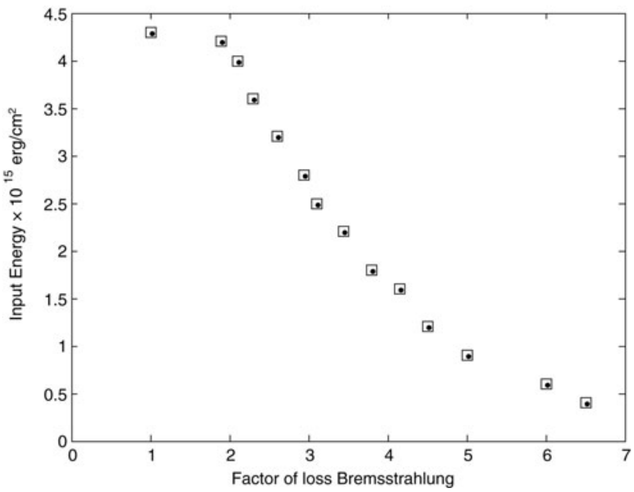

Fig. 2. Dependence of Input energy and bremsstrahlung loss with Collective effect for unignited case DT . Summary of the stopping length R for alpha particles depending on the plasma temperature $T = T_i = T_e$ and a set of plasma densities including the liquid – close to the solid-state for deuterium tritium DT at 5×10^{22} cm^{-3} for different binary interaction models collected by Stepanek (1981) showing the strong difference to the collective model (Ray & Hora, 1977). Factor of bremsstrahlung loss per generated fusion energy for side-on ignition of solid DT from the computation following Chu (1972) for input energy flux densities E* in the non-ignition range below the ignition threshold to demonstrate the then dominating losses by bremsstrahlung.

4. COLLECTIVE EFFECTS

The deposition of energy by alpha particles that are produced by DT laser driven fusion is important in calculations of the ignition and development of the inertial confinement fusion. The plasma is reheated by the collisions of the high energy alpha particles generated in the fusion reactions. The problem of reheat is involved with the very complex question, what penetration depth for the MeV alpha particles in the high density plasma is to be taken. Ray and Hora (1977) calculated it on the basis of a modification of the well known Bethe-Bloch formalism by Gabor (1952) and showed an increase nuclear fusion yields of inertially confined DT plasma due to reheat.

The basic physics responsible for slowing down of alpha particles is energy exchange through Coulomb interaction. This is a similar process for the treatment of the stopping power of alpha particles in plasmas following the Bethe-Bloch theory with several modifications by further authors as reviewed by Stepanek (1981) where binary collisions between the alphas, protons or other charged particles from nuclear reactions with electrons are considered. A visible discrepancy appeared with the measurements by Kerns *et al.* (1972) where an electron beam of 2 MeV energy and 0.5 MA current of 2 mm diameter was hitting deuterated polyethylene CD_2. The penetration depth of the electrons was measured by changing the thickness d of the CD_2, and the saturation of the emission of fusion neutrons at $d = 3$ mm was a proof for the very much shorter stopping length of the electrons than binary collision theories predicted. The energy loss rate of a energetic alpha particle to the DT plasma results from alpha-electron and alpha-ion interactions. The alpha-electron interaction is given by the Rutherford scattering cross section, and the alpha-ion interaction is given by the combination of the cross section of Coulomb and elastic nuclear processes.

An explanation of the value d was obtained (Bagge *et al.*, 1974) when Bagge's theory of the stopping of cosmic rays was applied where the interaction of the charged energetic particles was to be taken by the whole electron cloud in a Debye sphere for the electrons as discussed before by Gabor (1933, 1952). This collective model in contrast to the binary stopping power was treated by Ray and Hora (1976, 1977) based on kinetic theory using the Fokker-Planck equation and quantum electrodynamics.

The extreme discrepancy between binary and the collective theory of the stopping length of 3.5 MeV alpha particles in solid density DT is shown in Figure 3 following Ray and Hora (1977). For plasma temperatures above 0.1 keV binary Bethe-Bloch theory arrives at a stopping lengths R_{BB} given by the Winterberg approximation used by Chu (1972).

$$R_{BB} \propto T^{3/2} \tag{2}$$

In strong contrast to this binary stopping theory, the collective stopping length is nearly constant (Ray & Hora, 1977) for higher temperatures. The more precise expression taken

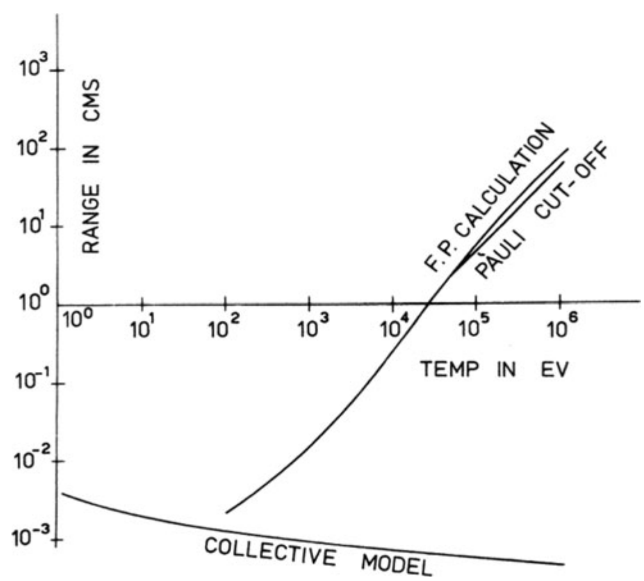

Fig. 3. Temperature dependence of the stopping length R (range) for alpha particles of 2.89 MeV in a fusion plasma of solid state density with binary electron collisions (Fokker-Planck F.P. collisions and quantum electrodynamic (Pauli) cut-off) and collisions with the electron collective in a Debye sphere (Ray & Hora, 1977) corresponding to the summary by Stepanek (1981, Fig. 6; Malekynia *et al.*, 2009, Fig. 1) where corrections to the binary collision theory with screened Debye potential according to the Gabor (1952) collective effect are included.

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from Fig. 3 is

$$R_\propto = \frac{e^2}{2kT}\frac{m_\propto}{m_e} Ei(\ln(\lambda E_0^2))\,\text{cm}(\text{temperature } T \text{ in keV}) \qquad (3)$$

taking into account the very slight decrease of R at higher temperatures T (Ray & Hora, 1977). Where Ei was given by Hora and Ray (1978) and E_0 is the initial energy of alpha particle. For temperatures less than 0.1 keV, the later extensions of the Bethe-Bloch theory and the collective theory resulted in nearly the same stopping lengths, see Figure 6 of Stepanek (1981). This result of the much shorter stopping length of the reaction products in laser fusion was the reason of the strong reheats in laser irradiated fusion pellets for DT at fully detailed inclusion of the adiabatic expansion dynamics of the spherical plasmas leading to the discovery of the volume ignition (Hora & Ray, 1978 Eq. (3) can be approximated by

$$R_a = 0.01 - 1.7002 \times^{-4} \text{T cm} \qquad (3a)$$

The Gabor theory (Gabor, 1952) of the stopping power of alpha particles for collisions with the whole collective of the electrons in the Debye sphere in contrast to the binary collisions with electrons following from the Bethe-Bloch theory, needed some closer consideration in view of results of volume ignition of spherically compressed pellets for fusion energy. As shown in Figure 3, the stopping lengths of both theories are not very much different for plasma temperatures up to about 100 eV (Stepanek, 1981), while the collective effect arrives at very different values for volume ignition at higher temperatures (Ray & Hora, 1977), see Figure 2 of Malekynia *et al.* (2009). This resulted in higher gains for DT fusion at volume ignition or the sub-ignition burn with spherical irradiation using the collective effect in agreement with measurements (Hora *et al.*, 1998). The experiments by Kerns *et al.* (1972) were a direct proof of the much shorter stopping length at very high intensity particle interaction which could immediately and convincingly be explained by the Gabor collective model (Bagge *et al.*, 1974).

The problems with the stopping power were observed by the experiments of Hoffmann *et al.* (1990) directly showing that the ranges of particle beams in laser produced plasmas are drastically reduced compared with the binary stopping theories. The complexity of the theories is well known (Stepanek, 1981; Deutsch, 1984; Deutsch *et al.*, 2007) but the experiments of Kerns *et al.* (1972) with the exact agreement to Gabor's results (Bagge *et al.*, 1974) and the measurements by Hoffmann *et al.* (1990) may be a basis for using the collective effect.

It was evaluated, what differences in the computations with the collective effect and without inhibition factor will appear with respect to the comparison of the new results (Hora *et al.*, 2008; Malekynia *et al.*, 2009) in comparison with the stopping power in the temperature range below 100 eV where Chu (1972) used the then not valid (see Fig. 3) Winterberg Eq. (2).

5. REVISED HYDRODYNAMIC COMPUTATIONS WITH THE COLLECTIVE MODEL

In order to see the importance of the collective effect of the stopping power in the hydrodynamic equations, we are comparing the results with the initial computations performed by Chu (1972). The correction by inclusion of the reduction of the thermal conductivity expressed by the inhibition factor was presented before (Ghoranneviss *et al.*, 2008), which discussion is separated from the present considerations.

The hydrodynamic equations used are the same as presented before (Ghoranneviss *et al.*, 2008, Hora *et al.*, 2008) where for the reason of comparison with the results of Chu (1972) no essential changes were taken into account. The only differences are that the bremsstrahlung is based on the electron temperature T_e working with Eq. (15) from Chu (1972) with the maximum at $x = 0$, thus,

$$W_i + W_e = A\rho T_e^{1/2} + \frac{8}{9}(k/m_i)(1/aT_e^{1/2}) + \frac{2}{9}(T_e/t). \qquad (4)$$

Eq. (4) is a little different from Eq. (20) of Chu (1972) where $T_i = T_e$ is assumed while the following computation with the collective stopping has to be performed for general temperatures. The α particles are assumed to deposit their energy in the plasma. They have a mean free path at solid state density DT according to Figure 3 for the Ray-Hora case of collective effects given by Eq. (2). The action of the stopping with the collective effect is expressed by the temperature T from Eq. (2). For the calculation of the collective effect we added a term to right-hand of Eq. (3). Thus

$$W_i + W_e = A\rho T_e^{1/2} + \frac{8}{9}(k/m_i)(1/aT_e^{1/2}) + \frac{2}{9}(T_e/t) + P, \qquad (5)$$

where P is the thermonuclear heating rate per unit time obtained from the burn rate and the fractional alpha particle deposition including the loss Y of burned fuel.

$$P = \rho Q E_\alpha f \qquad (6)$$

$$\phi = \frac{dW}{dt} = \frac{d}{dt}\left(\frac{1}{2}n(1-Y)^2\langle\sigma v\rangle\right) \qquad (7)$$

$E_\alpha = 3.5$ MeV and f is the fraction of alpha particle energy absorbed by electrons or ions, which has been given by

$$f_i = \left(1 + \frac{32}{T_e}\right)^{-1} \text{ and } f_e = 1 - f_i. \qquad (8)$$

For the equations after Eq. (4), the temperature of the electrons and of the ions were used to be equal to T, as used in Eq. (2) for the following numerical evaluations. These relations had to be repeated from before because we

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are using the exact stopping length from the collective theory (3) for comparison with the approximation (3a) in the following numerical evaluations.

6. NUMERICAL RESULTS WITH INCLUSION OF THE COLLECTIVE EFFECT

The following numerical evaluations are reported where the development of the temperature with the time t is used in order to compare the ignition condition with the results of Chu given in his Figure 2 (Chu, 1972). The here presented Figure 4 shows a lower set of curves that are very similar to that of Chu where all his conditions are the same with exception of the use of the temperature T_e instead of the ion temperature T_i because of dependency of the bremsstrahlung and thermal conductivity to T_e. Figure 1 also contains the new results with inclusion of the collective effect leading to higher temperatures as expected from the shorter stopping length using the same irradiation energy flux densities as in the cases of Chu for ignition given as E^* in erg/cm^2. Chu found that ignition happens at $E^* = 4.3 \times 10^8\ \text{J/cm}^2$ for the case without collective effect as seen here too from the time dependence of the curve continuing to be constant on time. For higher E^*, the curves for the temperature are still increasing in time. It was evident that the evaluation was to some extend difficult where the more precise threshold values are to be found because the characteristic curves in Figure 1 had to be followed up for long times to check whether there is a very slight increase or decrease on time. Figure 4 shows the result for longer times than reported before and for a higher resolution of the ordinate. It turned out that the convincing result for ignition at inclusion of the collective effect without the inhibition factor is at E^* at $2.5 \times 10^8\ \text{J/cm}^2$ and the exact threshold is at a little lower E^* value.

The results of Figure 1 and 4 including the collective effect were using the linear approximation (Eq. (2)) Malekynia *et al.* (2009). We checked what differences appear if the exact formulation (3) is used (Fig. 5). The differences to the linear approximation of the slightly bent curve for the collective stopping is very small (Fig. 3) and are very close to the various different derivations of stopping ranges summarized by Stepanek (1981, Fig. 6; Malekynia *et al.*, 2009, Fig. 1) where corrections to the binary collision theory with screened Debye potential according to the Gabor (1952) collective effect are included. A difference appears when instead of the linear approximation, the exact stopping lengths were now used as shown in Figure 5. The calculations with the exact stopping lengths of Eq. (3) arrive at little higher temperature than with the linear approximation. Although the differences are not very strong it is remarkable, what the very minor difference between the approximation and the exact stopping length is leading to. For lower E^* values than the threshold, the difference of the results with approximated and exact stopping length are seen to be stronger. This may be due to the fact that in the range much below the threshold, the losses by emission of bremsstrahlung is much stronger against the generation of fusion energy.

It is important to note that in all these results, that of Chu, that with collective effect only (Malekynia *et al.*, 2009 and the here presented results), and with collective effect and inhibition factor, the plasma temperature with ignition of DT is always higher than 4 keV. This is the well known limit above which the fusion energy only can be higher than the bremsstrahlung. This is understandable because the side-on ignition is generated in interaction fronts of the fusion flame (according to the terminology of Bobin, 1974) where the involved volume is so thin that neither

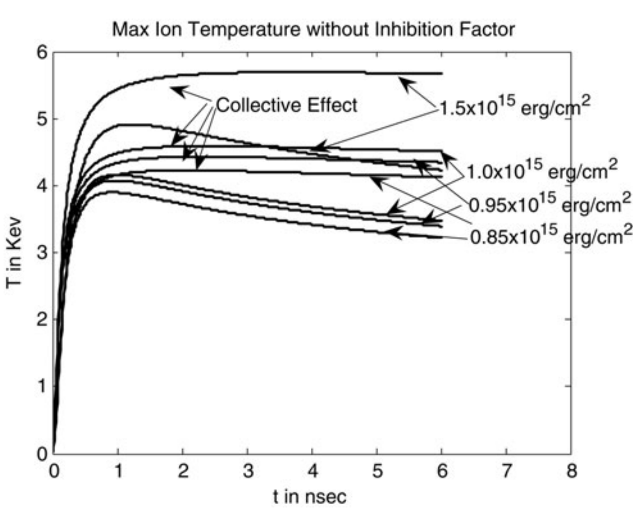

Fig. 4. Results as in Figure 1 showing ignition of solid deuterium tritium with the collective effect being reduced by about a factor 4 to $E^* = 1.05 \times 10^8\ \text{J/cm}^2$.

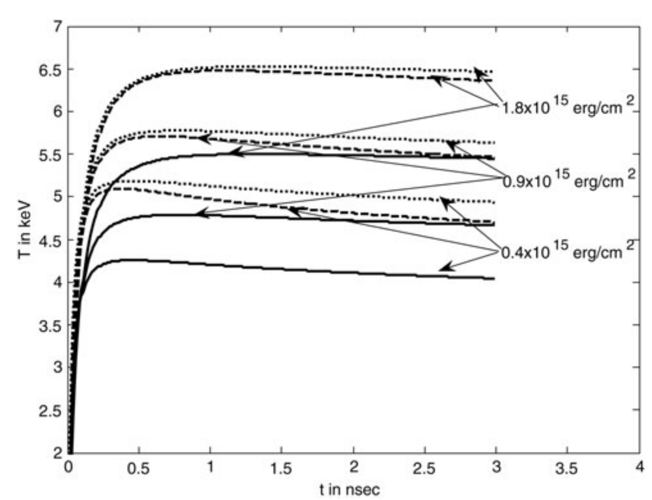

Fig. 5. Max Ion Temperature without Inhibition Factor For The Unignited Case Side-on ignition characteristics for solid DT for E^* as parameter. The lowest of each of the three plots is without collective effect, the upper very close lines show the use of the approximation of the collective stopping, Eq. (2) while the highest lines uses the un-approximated values from Figure 3.

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re-absorption of bremsstrahlung nor additional heating in the plasma by the reaction products (re-heat) can have an effect. This is different for the larger volume effects with the spherical laser compression scheme, where re-absorption and re-heat can lead to optimum ignition conditions at much lower temperatures than 4 keV, even down to 500 eV (Miley *et al.*, 2005).

Based on the here elaborated results, the side-on ignition of proton-11 boron (HB11) fusion was studied and reported separately (Hora *et al*., 2009*a*, 2009*b*).

It should be realized that the new direction for laser driven fusion energy by side-on ignition with nonlinear force driven plasma blocks is just at the beginning to be explored (Hora, 2009; Hora *et al.*, 2009*a*, 2009*b*) and general difficulties may appear at further studies when other methods than hydrodynamics are used. The anomalous generation of plasma blocks by interaction of petawatt-picosecond laser pulses permits side-on ignition of uncompressed solid fusion fuel. After application of the Chu-model for deuterium-tritium and including of the inhibition factor for thermal conduction (Ghoranneviss *et al.*, 2008; Zhou *et al.*, 2008), the studies for the reduced stopping lengths for alpha particles are extended here continuing the preceding considerations (Malekynia *et al.*, 2009) including a detailed description of the hydrodynamic properties with application of the generally rather complex theory of the stopping power. The separate elaboration of the collective effect compared with the inhibition factor was needed for a detailed understanding in view of the complexity of the stopping power theory, after first results of the combination of the collective stopping with the inhibition effects were summarized (Hora *et al.*, 2008) and the influence by losses of bremsstrahlung at non-ignition conditions below the threshold were understood. The fact has to be underlined that the ignition temperatures for all the considered fuel are above the energy loss by bremsstrahlung as known since the computations by Chu for DT and as it was repeatedly confirmed in the present treatments. This emission was based on collective effect stopping power of alpha particles.

The side-on ignition is a process in a shock front with energy production from the ions and the generated alpha particles. These conditions are determined by thin volume geometry of the side-on ignition where the advantages of the volume ignition at spherical laser fusion are not possible. The problem is that the here reported hydrodynamic analysis is based on one dimensional plane and infinitely extended geometry. In reality there is a lateral spread of the interacting laser beam though this is of a radius in the dimension of thousand laser wave lengths. A number of these geometries have been evaluated by Bobin (1974) and a first reference to these results may confirm that the better conditions for the nonlinear force driven block ignition of HB11 by several orders of magnitudes in contrast to the spherical laser compression scheme may sustain the further analysis (Hora *et al.*, 2009*a*, 2009*b*).

The here elaborated result about the stopping length of alpha particles from the DT fusion reaction relates to a kind of a delta function or at least of a layer with highly reduced thickness. We know from Figure 3 and related theories based on Gabor's (1933; 1952) collective model that the stopping length of alphas of about 3 MeV energy in plasmas of any subrelativistic temperature is in the range between 0.001 and 0.008 cm to explain the validity of the one-dimensional hydrodynamic analysis beginning with Chu (1971) and Bobin (1974). This is in essential contrast to the three-dimensional problems of the electron beam ignition with the Nuckolls-Wood (2002) method. The three-dimensional discussion of Nuckolls and Wood is then based on the volumetric (see page 4 of Nuckolls *et al.*, 2002) ρR criterion where ρ is the density of plasma uniformly compressed in a sphere of radius R. This criterion was derived from the numerically calculated optimum fusion gains G (Hora *et al.*, 1970; Hora & Pfirsch, 1972) giving the fusion energy per input laser energy E_0 into a spherical volume with radius R of fusion fuel of density ρ per solid state density ρ_s

$$G = (E_0/E_{BE})^{1/3}(\rho/\rho_s)^{2/3} = \text{const} \times \rho R \tag{9}$$

where E_{BE} is the break even energy with the value 6 MJ for DT. The first expression of (9) was formulated in 1970 (Hora *et al.*, 1970) and the second, resulting from $E_0 \sim \rho R^3$, was first published by Kidder (1974). This is the result of volume burn at spherical uniform compression according to the self-similarity model (Hora, 1981, Section 5) only at optimum temperatures (of 11.5 keV for DT) and is valid only up to gains $G < 8$ for DT (Hora *et al.*, 1998). For higher gains, volume ignition was discovered (Hora *et al.*, 1978), confirmed by Wheeler modes (Kirkpatrick *et al.*, 1971), where other gain formulas were derived for higher gains (Hora, 1987; Betti, 2009) apart from the detailed numerical diagrams (1998). Under these special conditions, the ρR formula (9) can be used for three-dimensional geometry only. The side-on ignition by nonlinear force driven plasma blocks with the generation of shock fronts as fusion flames (Hora, 2009) is a one-dimensional problem and not that of three dimensions as in the case of electron beams (Nuckolls *et al.*, 2002) with few mm stopping lengths of the electrons as measured (Kerns *et al.*, 1972).

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