Fusion energy without radioactivity: laser ignition of solid hydrogen–boron (11) fuel

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The advent of ultra-high power lasers allows laser power levels that are about 1000 times the power of all the power stations in the USA. This opens the way to new approaches for inertial confinement fusions (ICF) that in turn can drastically reduce the laser input energy needed to achieve practical ICF power. The specific approach discussed here involves inducing a fusion burn wave by laser-driven impact of a relatively large block of plasma on the outside of a solid density fusion target. This new method is specifically selected to enable the extremely attractive, but demanding, neutron-free proton–B-11 fusion that potentially can lead to the long sought goal of an ultra "clean" fusion power plant.

1. Introduction

Strategies being proposed to reduce fossil energy sources to avoid global warming generally involve mixes of renewable energy sources and nuclear fission. In the long term, however, the radiation problems of radioactive waste disposal for fission power must be solved with rather complex technology. Fusion is not yet a contender in this mix, due to the perceived long time scale for fusion development. However, it is anticipated at the National Ignition Facility (NIF) in the USA[1] that this should change quickly when ignition of an inertial confinement fusion deuterium–tritium (ICF DT) target occurs in several years time. This ICF power using deuterium–tritium (DT) fuel would eliminate long term radioactivity, but still involves radioactive tritium and neutron-induced radioactivity in the plant structural materials. Producing fusion energy with radioactive emission levels lower than the levels for burning coal (which is so low that radioactivity due to impurities is usually ignored) has been thought to be impossible due to the demanding ignition requirements the hydrogen boron-11 (H–^{11}B) fuel needed to achieve this goal. The problems and requirements for H–^{11}B fusion were first discussed in detail in an early book published by one of the authors.[2] However, recent research now opens up this possibility by using a new scheme for laser ignition involving a "block plasma" ignition technique.

Laser driven fusion has rapidly advanced in recent years based on continuing clarification of the key physics problems, allowing experiments to progress to the point where DT ignition is expected. The long term goal of all ICF research is to produce clean, greenhouse gas free, and safe energy using inexhaustible fuel which is available to all nations. The NIF laser is expected to produce ignition by delivering pulses of 1.1 MJ on the ICF target over a few nanoseconds.[1] The ignition campaign at NIF is scheduled to achieve ignition in 2010–2011, demonstrating for the first time on Earth a controlled fusion reaction capable of generating more energy than delivered by the input laser pulse. The DT fusion reaction burns (reacts with) isotopes of heavy hydrogen (deuterium, D) with the super-heavy hydrogen isotope (tritium, T), where the laser irradiation compresses the fuel to

Broader context

After 50 years of research on fusion energy within the United Nations program on "Peaceful use of Nuclear Energy", a new opportunity is now emerging to use fusion energy while avoiding any radioactive radiation above the level of burning coal. This remarkable approach is made possible by using laser pulses of picosecond (ps) duration and several petawatt (PW) power to burn hydrogen-boron 11 (H–^{11}B) fusion fuels. This fuel uses plentiful light hydrogen (H) and the boron isotope 11 (H–^{11}B, or alternately termed p–^{11}B) reaction which yields energetic charged particles without generating neutrons. The usual laser compression developed for burning deuterium–tritium (DT) fuel cannot be used for H–^{11}B because densities of 100 000 times the solid are needed. Instead, the alternative laser fusion scheme of side-on ignition with uncompressed fuel is proposed to enable ignition of the H–^{11}B fuel along with PW laser interactions. This approach employs a recently discovered laser-plasma interaction technique that uses very high contrast ratio laser pulses (*i.e.* pulses nearly free from pre-pulses). Plasma blocks of modest temperature are generated causing highly directed ion current densities above 10^{10} A cm^{-2}. This new ignition process is termed "side-on block ignition", and it is described here in some detail.

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more than 1000 times the solid density, causing heating to ignition temperatures of several tens of millions of degrees centigrade. Following on this success, LLNL scientists have proposed a prototype power station[3] for 2020, based on use of a very compact, high efficiency, and high repetition rate diode pumped laser which builds on current laser technology. Simultaneous development of a power plant using similar technology is also proposed for use as an actinide burner to resolve the radioactive waste problem from existing light water reactors.

Parallel to these developments, new schemes for ICF power have been proposed based on the new type of laser[4] offering more than PW (petawatt) pulses[5,6] over picoseconds. The basic scheme is to use a slower pulse laser to initially compress a target to reasonably high density and then use this PW laser to heat (ignite) some volume in the target, which will burn into the rest of the high density fuel. Called "fast ignition" (FI), this method significantly reduces input power requirements, hence giving higher energy gain operation. If achieved, this approach promises a higher performance power plant than possible with the conventional direct compression and burn of the ICF operation. For one of these FI options, a design by Nuckolls and Wood[7] using electron beam ignition, initial compression to only about 10 times solid state density is needed. The ignition occurs with very intense electron beams (of 5 MeV energy). These PW laser beams interact with the pre-compressed target through highly non-linear effects. This technique arrives at fusion gains of 10 000. A pre-compression of the target to about 1000 times solid-state density is required to generate the intense electron beam.

This paper now reports on another method[8] that uses PW–ps laser pulses without high pre-compression of the target. It uses side-on ignition of the target at normal solid state or slightly increased density. The technique follows mechanisms which were actually observed in 1972.[9,10] However, according to these early results, it appeared impossible to use this in a practical system. This pessimism came from recognition of the enormous energy flux densities predicted. Analysis suggested the exorbitant threshold E_t^*.

$$E^* > E_t^* = 4 \times 10^8 \text{ J cm}^{-2} \qquad (1)$$

As a result this "side on" ignition scheme[9,10] was ignored and the direct spherical laser irradiation of DT plasma became the favored route in labs around the world.

More recently with the advent of 2 PW–ps lasers, focus has begun to shift to FI techniques.[5,6] However, the early results from studies of PW laser of interactions with ICF targets proved to be quite complex, evoking the need for an improved understanding of the interaction physics. Following the first experiments,[6] it was found in many laboratories that extreme relativistic effects resulted in a "maze" of new effects; *e.g.*, positron bursts from pair production, intense gamma bursts leading to nuclear transmutations, generation of very intense electron beams or beams of highly ionized ions with energies beyond the GeV range.

Section 2 explains how an anomaly with the PW–ps laser pulses was subsequently discovered based on use of extremely clean laser pulses (*vs.* the conventional case where a low level intensity hits the target just before the full pulse arrives). Based on the discovery of this effect it now appears that the exorbitant laser flux densities of eqn (1) for pulse durations in the ps range can be obtained for side-on ignition of uncompressed DT. This is explained along with exploratory hydrodynamic computations based on ref. 9 and 10 with generalizations and extensions[11] in Section 3. Section 4 explains the long term advantages for fusion of protons (*i.e.* hydrogen, H) with the boron-11 (^{11}B) isotope, and how, in contrast to the spherical laser ignition, side-on ignition can be employed to ignite H–^{11}B fusion fuel (Section 5).[11,12] Section 6 discusses some clarifications of the physics derived from the results of the hydrodynamic model. This leads into a discussion of how future research is needed to bring the new side-on ignition physics and technology to the same level of maturity as traditional spherical ignition.[1] Indeed, side-on ignition becomes the enabling feature in the path to use H–^{11}B fuel to achieve the goal of fusion energy generation with less radioactive radiation than from burning coal. Much more work is needed, however, to fully understand this radical new approach. Thus, modifications arising from not yet explored effects and mechanisms may occur, but the initial results reported here appear very promising and leave some room for error in view of the several orders of magnitudes improvement offered over the conventional spherical compression.

2. Come-back of Bobin and Chu type side-on ignition

The following scheme for generation fusion energy is based on measurements observed as an extreme anomaly during interaction of ps or shorter PW laser pulses. This was understood from much earlier numerical studies for laser plasma interactions[13] (see ref. 14 Chapter 10) showing in one dimension, the action of the nonlinear (ponderomotive) force[15] due to dielectric plasma effects[16]). The exact measurement of the predicted acceleration of plane plasma fronts was not possible until 1996[17] because analysis of all preceding measurements[14] assumed plane geometry, which was invalid due to relativistic self-focusing[18] (see ref. 16 Chapter 12). Self-focusing resulted in acceleration of highly charged ions of MeV to GeV energy. The first experiments that avoided self-focusing were carried out by Sauerbrey.[17] He cut off

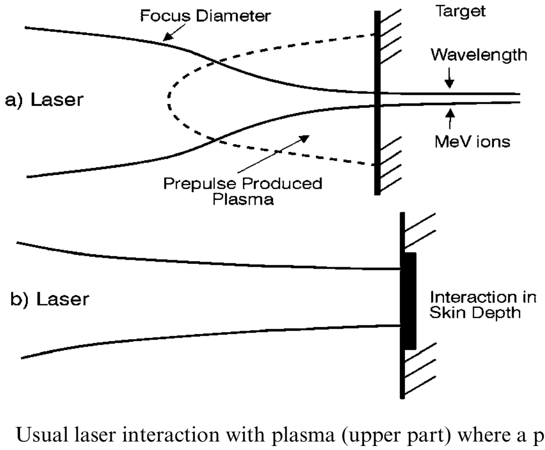

Fig. 1 Usual laser interaction with plasma (upper part) where a plasma plume is generated by the pre-pulse which squeezes the laser beam to wave length diameter due to relativistic self focusing while (lower part) suppression of any pre-pulse by high contrast ratio (right) provides a plane geometry interaction.

the laser pre-pulse (giving a high contrast ratio $>10^8$) over ~50 ps before the main pulse interacted with the target (see Fig. 1). This prevented the generation of a plasma cloud (plume) in front of the target which generates the relativistic self-focusing effect and associated laser beam filamentation. With clean laser pulses, no beam filamentation could occur. Instead block plasma formation was found. This block effect was termed an "anomaly", although it turned out to be in agreement with prior nonlinear force theory.[19]

Measurements of ions emitted from a target by Badziak *et al.*[20] under same "anomalous" conditions used by Sauerbrey indicated maximum ion energies of 0.5 MeV while, in sharp contrast, relativistic self-focusing without a clean laser pulse would have produced 22 MeV ions. This anomalous effect was also shown the experiments by Zhang *et al.*[21] using an X-ray emission diagnostic. The "normal" intense hard X-ray emission was suppressed with very clean (*i.e.* high contrast ratio) 0.5 ps laser pulses. When a small part of the main pulse was pre-irradiated at times t^* before the main pulse, the X-ray emission was suppressed for $t^* < 70$ ps. Then for longer times X-ray emission suddenly increased up to the high levels observed in other experiments without a high contrast ratio laser. It was later realized that the 70 ps delay just corresponded to the time needed for building up the plasma plume in front of the target (Fig. 1). The theoretical understanding of this emerged in 2002 in terms of the nonlinear force acceleration of the dielectrically enlarged skin layer.[22] Many details of this theory were confirmed later experimentally and numerically.[19] Subsequently, high contrast ratio laser studies by Badziak *et al.*[20] measured highly directed energetic charged ions moving in quasi-neutral plasma blocks of modest temperature and ion current densities above 10^{11} A cm^{-2}. The potential use of such ion beams for igniting laser driven fusion was immediately realized from the earlier computations[13,14] as a skin layer process (formulated in 2002 by the first author in a patent application[23] which was declassified along with a similar case with electron beams[7]).

3. Chu's threshold prediction for side-on ignition of solid deuterium–tritium

The use of nonlinear force driven plasma blocks with the ultrahigh current densities using a PW–ps laser-plasma interaction permits a come-back of the side-on ignition of uncompressed DT. Indeed, "side-on" ignition was extensively studied with hydrodynamic computations by Chu in 1972.[9] Chu's work was later confirmed by Bobin in 1974.[10] This hydrodynamic analysis used very general assumptions, including energy losses by Bremsstrahlung emission and a shock-front theory[24] that showed the basic character of chemical detonation derived earlier by Döring and von Neumann. The present results are largely based on an extension of the work of Chu[9] as explained and elaborated on in detail in ref. 11 and 25. Most updating involved inclusion of the new "anomalous" phenomenon discussed earlier, which was not known in 1972[11] when Chu did his work.

Side-on ignition for fusion using plasma blocks driven by nonlinear forces laser interactions is based on preventing self-focusing of the laser beam as previously described. This requires strong suppression of laser pre-pulses, *i.e.* a contrast ratio higher than 10^8, for times dozens of ps before arrival of the main pulse. The resulting plasma blocks have high momentum and are directed back towards the incoming laser beam. Momentum conservation causes an imploding block of plasma towards the inner portion of the target fuel. This implosion produces an inward moving thermonuclear reaction shock front as elaborated in the work by Chu.[9] If the laser is obliquely hitting the plane target, the direction of the nonlinear force accelerated blocks is mainly perpendicular to the target surface, with minor deviations due to collision absorption,[26] anticipating the later derived TNSA (target normal sheet acceleration) by Wilks from his discovered particle-in-cell computations (see Badziak 2005[19]).

The theory of creation of the high velocity quasi-neutral plasma blocks is based on skin-layer acceleration by nonlinear forces.[19,22,23] Because the acceleration of the ions is electrodynamic,[16] and not thermo-kinetic, the observed blocks (pistons) are highly directed and have a comparably low temperature. The DT ion beam current density j in the space charge neutral block must exceed a threshold value j^* to create fusion reaction waves in solid DT fusion fuel.[9] Thus;

$$j > j^* = 10^{11}\ \mathrm{A\ cm^{-2}} \tag{2}$$

However, another necessary condition for the side-on ignition is that the energy flux density E^* must exceed a threshold E_t^* for DT with an ignition temperature T_{ign}. In summary, according to the hydrodynamic analysis by Chu,[9] the energy flux must satisfy the condition:

$$E^* > E_t^* = 4.3 \times 10^{15}\ \mathrm{erg\ cm^{-2}};\ T_{\mathrm{ign}} = 7.2\ \mathrm{keV\ (DT)} \tag{3}$$

This can be seen in Fig. 2, which depicts Chu's results of the generated maximum temperature $T(t)$ in irradiated solid DT *vs.* time t. As soon as $T(t)$ merges into a constant time dependence, the threshold E_t^* is reached.[25] A recent updating of Chu's calculations with inclusion of a reduced thermal conduction between hot and cold plasma given by an inhibition factor F^* (attributed to the electric double layer) and including a collective effect for the stopping length of the alpha particles, resulted in a decrease of E_t^* by a factor of 20.[11] Though this value is still very

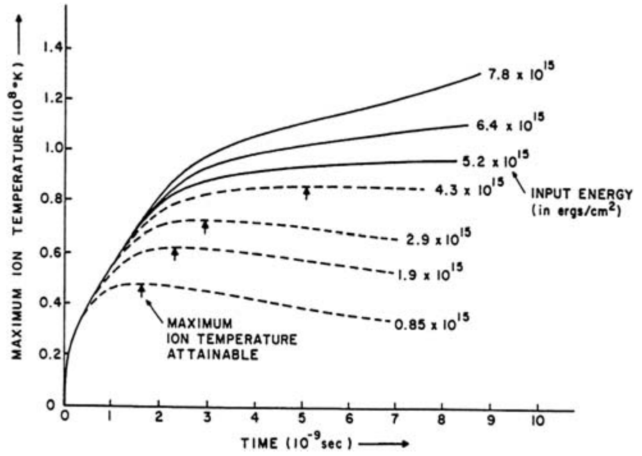

Fig. 2 Characteristics of the maximum temperature T on time t for parameters E^* of energy flux density in ergs cm^{-2} for side-on fusion ignition of solid state DT from Fig. 2 of Chu.[9]

high, it is not too far from the experimental conditions predicted from extrapolation of present experiments[19] to next generation PW–ps laser pulses.[5]

To evaluate the details of these new effects, we recalculated the side-on ignition of DT under the conditions assumed by Chu. The calculations were very close to those of Chu, Fig. 2.[25] Next, the reduction of E_t* by the inhibition factor was evaluated. Extensive theory about the inhibition and the collective effects has been presented in other publications,[8] based on double layer theory.[27,28] These results were used for to obtain a fit for appropriate inhibition factors F*. With these new computations of the DT reaction, it was possible to also include a detailed evaluation of the Bremsstrahlung emission. As a benchmark, it was shown that use of the method for Bremsstrahlung emission arrived at the well known temperature of 4.3 keV for "ideal energy breakeven" of DT fusion. The hydrodynamic formulations are mostly taken over from the treatment of Chu[9] as reported before.[11,25] Detailed publication of the complete computer code including appropriate comments are being prepared for a journal on computation science.

4. Hydrogen–boron fusion with negligible radioactivity

In the electron beam scheme of Nuckolls *et al.*,[7] the scheme for side-on block ignition proposed can not work without the need of initial plasma pre-compression. However, the present scheme is based on the generation of extremely intense ion beams. The new scheme is therefore a single step interaction PW–ps laser irradiation process that works with uncompressed DT fuel or with modest compression similar to the electron beam scheme. These results show the promise of side on ignition of uncompressed DT compared to the well known scheme of spherical laser compression and ignition. Before extending side-on block ignition from DT fuel to ignition of H–^{11}B fusion, we need to acknowledge some key difficulties which are discussed next.

From the beginning of fusion energy research, a long term goal has been to use the unique H–^{11}B reaction:

$$\mathrm{H} + {}^{11}\mathrm{B} = 3\,{}^{4}\mathrm{He} + 8.664\ \mathrm{MeV} \tag{4}$$

since it results in the production of MeV alpha particles and no neutrons by bombarding boron targets with protons of energies up to 150 keV.[29,30] The energetic alpha particle products are ideal for highly efficient direct conversion into electricity to achieve a reduction in waste heat pollution.[2] The produced alpha particles can also be collimated with magnetic fields for space propulsion.[2,30] Secondary reactions lead to some H–^{11}B radioactivity but this is less per unit of energy produced than burning coal,[31] which naturally contains 2 ppm uranium. However, it has been evident from the beginning that the H–^{11}B fusion reaction is much more difficult to achieve than using deuterium–tritium (DT) fusion fuel, as seen from the relative reaction cross sections. Also early calculations assuming spherical laser compression of H–^{11}B required extreme densities of 100 000 times the solid state[32] and input laser pulses of some 10 MJ energy to produce modest energy gains per laser energy of less than 25.[33] These conditions are exorbitant and seemed to exclude any hope for laser driven H–^{11}B fusion. Now, the new developments involving block and side-on ignition described here may get around these difficulties. This would lead to the first kind of clean energy production without any of the prior environmental disadvantages of nuclear energy.

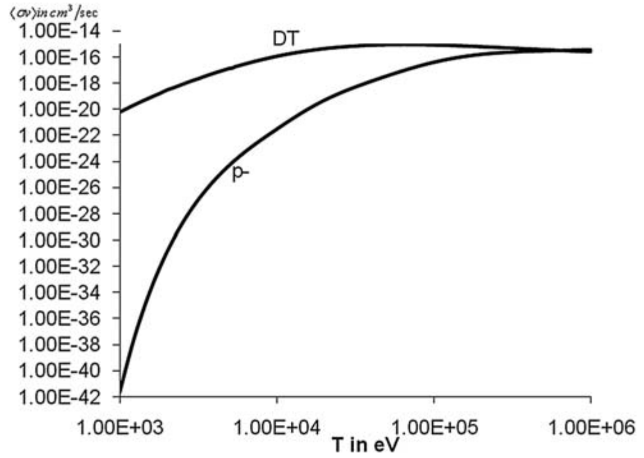

Fig. 3 Fusion reaction rates for DT and for H–^{11}B depending on the plasma temperature T.

5. Side-on block ignition threshold for hydrogen boron

To confirm consistency with the results of Chu[9] with DT fuel, computations were first performed based on his assumptions. Using the H–^{11}B fusion reaction rates given by the reaction cross section σ was averaged for a temperature T over a Maxwellian distribution of the velocity v of the particles. Fig. 3 shows the rates for the DT reaction together with that of the H–^{11}B reaction used in the hydrodynamic calculation. This results in the time dependence of the plasma temperature shown here in Fig. 4 in comparison to Fig. 2 for DT. The parameter of the curves is the energy flux density E*. What is important is to find the value of E_t* (ignition threshold) where the plasma temperature T merges

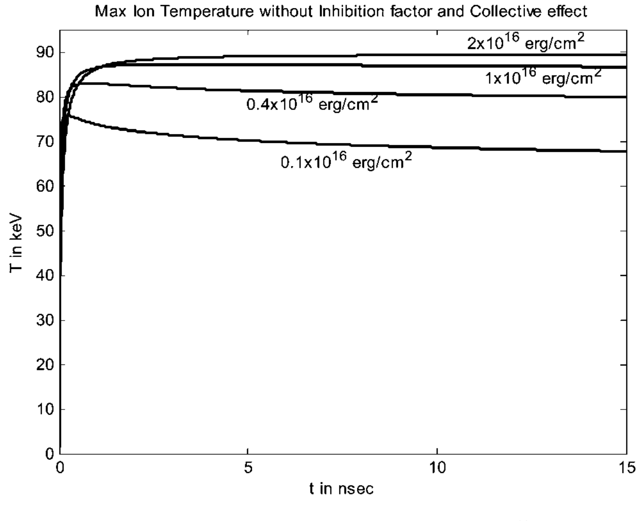

Fig. 4 Characteristics of the kind of Fig. 2 for H–^{11}B under the assumptions most similar to Chu[9] for comparison with DT fusion.

into a constant value after longer times, *t*. In order to define the threshold E_t^* for H–^{11}B, the computation of the temperature T in Fig. 4 was run for a comparatively long time (15 ns) in order to determine the stationary values. From these results, it can be estimated that the final value is approximately

$$E_0^* = (1.0 \text{ to } 2.0)\times 10^9 \text{ J cm}^{-2};\ T_{\text{ign}} = 87 \text{ keV (H–}^{11}\text{B)} \quad (5)$$

These results appear to be very modest compared with the values of DT, eqn (3), according to Chu,[9] Fig. 2. In view of the exorbitant difference between DT and H–^{11}B for volume ignition based on spherical pellet compression, it is truly surprising how much easier the ignition of H–^{11}B works for a side-on generated thermonuclear reaction wave. Part of the explanation can be obtained from Fig. 3, which shows that the $<\sigma v>$ values for DT and for H–^{11}B are reasonably close for their respective ignition temperatures.

The correctness of the hydrodynamic results shown is supported by the consistency observed in the resulting temperatures. In the case of DT, the energy averaged value ignition without reheat and without partial X-ray re-absorption falls from about 12 keV for spherical compression to 7.2 keV even under the simplified conditions of Chu,[9] eqn (3). There is a clear similarity to the case of p–^{11}B. There, the temperature for the spherical compression without reheat and without partial self-absorption is in the range of 150 keV,[32,33] while the present side-on ignition of solid fusion fuel is ~87 keV for the side-on ignition with the assumptions of Chu,[11] Fig. 4 and eqn (5).

In summary, the basic result of this work is to confirm that side-on ignition of uncompressed H–^{11}B fuel is not very much more "difficult" than DT fusion. Further, it is estimated to be possible with laser pulses in the range of ps duration and several dozens of PW power, after 10 PW pulses have been produced (see Dunne[5]). Some slight pre-compression by chemical explosives[7] or the inclusion of other effects, such as thermal flux inhibition may cause a further reduction of these requirements.

Among the numerous further details to be evaluated, we report here about one updating modification of Chu's,[9] namely the reduced thermal conduction in the extremely inhomogeneous plasmas. This effect has traditionally been handled using an inhibition factor F^*. This factor was evaluated before for DT.[11,25] The theoretical background was based on the creation of an electric double layer, which reduced electron flow. An inhibition factor $F^* = 106$ was introduced here for H–^{11}B and the hydrodynamic computation of Chu[9] was repeated. The results for H–^{11}B are shown in Fig. 5. The factor F^* is based on the theory of electron depletion in the electric double layers, reducing the thermal conductivity by the square root of the electron mass to the ion mass which was expressed by the average ion mass. Due to the lower thermal conduction, the threshold energy flux density E^* is reduced to 7.7×10^8 J cm^{-2} compared with eqn (5). Further details of these theoretical studies were given previously.[11,12,25]

These computations also showed that Bremsstrahlung radiation losses were reasonably low for both DT and H–^{11}B cases. Otherwise ignition could not have been obtained beginning with the plots of Chu,[9] Fig. 2, or for the H–^{11}B case presented here in Fig. 4 and 5. Bremsstrahlung is not nuclear radiation, but is caused by electron slowing during deflection by charged ions; it typically falls in the 100s of keV range *vs.* MeV gammas. Since the Bremsstrahlung radiation emitted falls into the X-ray range of energies it can easily be stopped from escaping the reaction chamber by a modest shield.

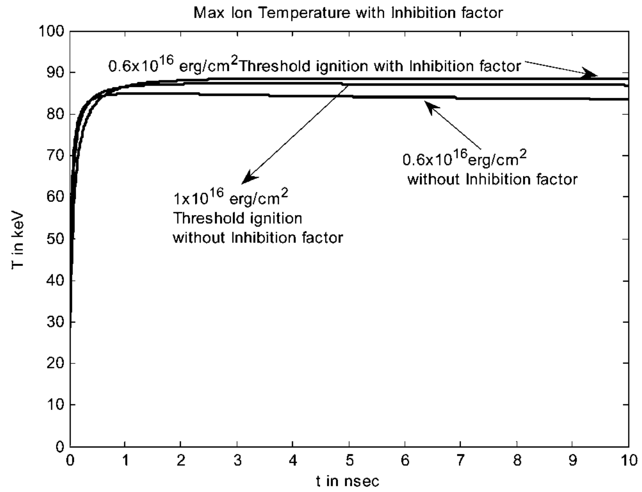

Fig. 5 As Fig. 4, with inclusion of reduced thermal conduction due to the inhibition factor F^*.

6. Discussion

Side-on ignition for fusion energy using nonlinear force acceleration of plasma blocks by PW–ps laser pulses is clearly a new frontier. In comparison with the matured scheme of spherical laser compression, there are still a number of issues/questions to be answered. These concerns will be addressed in due course, as an extensive experimental program for clean PW–ps laser interactions with solid targets is combined with an appropriately diversified theoretical-numerical project. Results clarifying the dielectric properties of the resulting plasmas will be of special interest for understanding the basic phenomena involved.[34–36]

Much clarification is also needed to fine tune Chu's[9] hydrodynamic approach for this new approach. While Chu's results[9] were fully confirmed by Bobin,[10] his initial analysis[37] covered a wider range of problems concerning the characteristics of the radiation wave at the deflagration front between the intermediate medium, the hot plasma, and the buildup of shocks at the inner boundary. At the time of this analysis,[37] neither the experimental observation of thermal conduction inhibition in inhomogeneous plasma nor problems involved with electric double layers were known and were thus ignored.[8,27,28] These effects must be included properly to accurately evaluate the minimum time of electron thermal conduction for the deflagration structure [see eqn (69) of ref. 37]. This minimum time is estimated for DT to be about 2 ps, and 75 ps for H–^{11}B, but these results will be reduced by inclusion of the inhibition factor. Another question involves the conditions required for stability of the flow that revolve around the sonic particle velocity necessary for creation of a steady-state deflagration wave structure.

Other classes of problems that cannot be handled by ideal hydrodynamic need to be studied using other methods (*e.g.* ingenious particle tracking models developed by Wilks, *et al.*,[38] into modified particle-in-cells (PIC) techniques). The issue of interpenetration between very hot and cold plasma particles[39] may actually lead to an improvement in sub-relativistic temperatures and sufficiently small Debye lengths for the block description with electric double layers.[16,27] Noticeable differences were previously observed between the genuine two-fluid hydrodynamics and PIC results (ref. 40, Table 1). However, the compatibility of hydrodynamic results derived from the genuine two-fluid model[41] with PIC studies[42] was discussed at the sub-relativistic interactions arriving at a good agreement. The advantage of PIC is well known for relativistic laser intensities.[43] However, this intensity range is far beyond the sub-relativistic interaction range, just below the relativistic threshold for the nonlinear force generation of the plasma blocks for the side-on ignition.

Another problem is that the hydrodynamic analysis is based on plane and infinitely extended geometry. In reality there is a lateral spread of the interacting laser beam, though this is a radius in the dimension of a thousand laser wavelengths. A number of these geometries have been evaluated by Bobin[10] and a first reference to these results may confirm that better conditions for the nonlinear force driven block ignition of H–^{11}B by several orders of magnitude, in contrast to the spherical laser compression scheme may sustain the further analysis.

Finally, a difference exists between the three-dimensional problems of the electron beam ignition with the Nuckolls–Wood method[7] and the ion beam dominated side-on ignition discussed here. Only one-dimensional problems of the radiation wave deflagration and the two-dimensional shock fronts are relevant and have been considered to date In contrast, the three-dimensional discussion of Nuckolls and Wood[7] is based on the 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[44] 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

$$G = (E_0/E_{BE})^{1/3}(\rho/\rho_s)^{2/3} = \text{const.} \times \rho R \tag{6}$$

where E_{BE} is the break even energy with the value 6 MJ for DT. The first expression of (6) was formulated in 1970[45] and the second, resulting from $E_0 \sim \rho R^3$, was first published by Kidder.[46] This is the result of volume burn at spherical uniform compression according to the self-similarity model (ref. 16, Section 5) only at optimum temperatures (of 11.5 keV for DT) and is valid only up to gains $G < 8$ for DT. For higher gains, volume ignition was discovered,[47] confirmed by Wheeler modes,[48] where other gain formulas were derived for higher gains.[49–52] Under these special conditions, the ρR formula (6) can only be used for three dimensional geometry. The side-on ignition by nonlinear force driven plasma blocks with the generation of shock fronts as fusion flames[10,37] is a two dimensional problem and not that of three dimensions as in the case of electron beams.[7] Gain formulas for more general conditions were derived by Betti.[53] A relation to the present nonlinear force acceleration scheme of ps nonlinear force driven directed plasma blocks to the shock ignition by longer thermalizing interactions has been noted.[54]

7. Conclusion

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 H–^{11}B can be ignited. This fusion energy generation with laser pulses in the range of few dozens of PW power and ps duration can achieve H–^{11}B power production. 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.[30] Modest pre-compression by chemical driving[7] or with high density cluster methods[55] could improve 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. 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.[57] The support of the IAEA activities was under the auspices of the IAEA Deputy Director General Dr Burkard and by Dr Mank.

Appendix - comments about computation

The computations here closely follow the one-fluid hydrodynamic model as described by Chu[9] where the complete set of equations were published in references 11 and 25 including the special modifications explained analytically with respect to the inhibition factor and the collective model for the alpha particle stopping power. The computer code in MATLAB program is added at the end of the Appendix. Very few differences were observed in comparison with Chu's results as discussed before[25] in the case of DT at the same conditions before improvement. The differences for H–^{11}B have been outlined here with respect to the fusion cross sections and the averaged ion mass according to the double layer model for the inhibition factor.[8] The following code was usually used for computation up to times t of 10 ps, see line 3 of the code. One exception is the result of Fig. 4 where the time was used up to 15 ps.

In order to be as close as possible to the work of Chu,[9] the hydrodynamics uses a one fluid description. This is sufficient for reproducing Chu's side-on ignition processes. A similar treatment was now used with the plasma blocks produced by the PW–ps laser pulse irradiation. This excluded several issues that needed further examination; namely how dynamically changing dielectric plasma properties within the extended skin depth during the plasma interaction is involved in generating the plasma blocks. For these studies, a genuine two-fluid hydrodynamic plasma model[27,41] was used and generally applied for plane interaction geometry.[56] This allowed that the skin-layer acceleration was concluded to be important earlier for the anomaly of the plasma block generation. Then, Rayleigh density profiles were specifically applied to the optimal irradiation conditions.[35,36]

Computation code in MATLAB:

```
clc
clear
t = 0.001e-9 : 0.01e-9:10e-9;
%(t is time in sec)
Ein= (1.8e15)*(1e-7);
%(Einput is in joule)
Ln = 1.2925e-24;
%Ln1=(1.89*((2/pi)^1.5)*(Me^-0.5)*(k^3.5))/Ke
%(Ln is: (e^4)*ln(landa))
Me = 9.11e-28;
Mi = 2.5*1.6726e-24;
k = 1;
Dens = 0.1964;
%(Dens is density)
ADens=((2/9)*(7.5)^0.5)/5e-9;
%(ADens is Factor of bremsstrahlung*density)
a=(k/Mi)*(8/9)*(1/(ADens*2.1115))
Ke = 1.89*((2/pi) ^1.5)*(Me^-0.5)*(1/Ln)*k^3.5;
%a = Ke*(2*Mi/(3*Dens*k));
n = 4.6969e22;
%(n is Solid state density of D-T)
Eth = Ein/1.6e-16;
%(Eth is in keV)
Bcoupling = 5*1.7125*exp(-807.26/((2e15)^(1/9)))/((2e15)^(7/
18));
e = Bcoupling*((1e7*Ein) ^ (7/18))/((1.7125)*exp(-807.26/
((1e7*Ein)^(1/9))));
%(e is Factor of recoupling of input energy to plasma)
E = 3500*(1 + 1/2 + 1/e);
Q = Mi*Eth/(1.5*Dens*k);
To=(5/18)*((4.5^3.5)*(2^-1.5)*((gamma(9/2))^2.5)/ 1(((5/
2)*(pi^(5/2))*((gamma(2/5))^2.5))))^(4/9);
Inhibitionfactor=(Mi/Me)^0.5;
Te0 = 0.01*(Mi*Eth)/(1*3*k*Dens);
Te = Te0+ ((((Q.^2).*Inhibitionfactor.)./(a.*t.)).^(2/
9)).*To.^(2/5);
Solve ('E*n*1.6e-7*3.7e-12*(T^ (-2/3))*exp (-20*T^ (-1/3))/
12*k-ADens*Te^(0.5)-1(8/9)*(k/Mi)*(1/a)*Te^(-0.5)-(2/9)*Te/
t','T');
Pretty (ans);
T= -(1000)./lambertw(-(0.15007505629691605e11).*
((9.0*ADens.* 1Te.*Mi.*a.*t.+8.*k.*t.+2.0*(Te.^1.5).*Mi.*a.)./
(E.*n.*k.*Mi.*a.*(Te.^0.5).*t.)).^0.5).^3;
Plot (t,T)
Hold on
%(1 is continue of before line)
```

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