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Laser fusion energy from p-^{7}Li with minimized radioactivity

M. GHORANNEVISS,[1] A. SALAR ELAHI,[1] H. HORA,[2] G.H. MILEY,[3] B. MALEKYNIA,[1] AND
Z. ABDOLLAHI[1]

[1]Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]Department of Theoretical Physics, University of New South Wales, Sydney, Australia
[3]Department of Nuclear, Plasma and Radiological Engineering, University of Illinois, Urbana, Illinois

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Abstract

The new possibility of side-on laser ignition of p-^{11}B with negligible radioactivity encouraged to study the fusion of solid state p-^{7}Li fuel that again turns out to be only about 10 times more difficult than the side-on ignition of solid deuterium-tritium using petawatt-picosecond laser pulses at anomalous interaction conditions if very high contrast ratio. Updated cross sections of the nuclear reaction are included.

Keywords: Laser fusion; Radioactivity

1. INTRODUCTION

The research about future options for controlled generation of fusion energy for power stations received an essential turning point by interaction of picosecond laser pulses of powers above terawatts with plasmas resulted in ultrahigh acceleration of plasma layers with a thickness of dielectric increased skin depths (Hora *et al.*, 2002). These plasma blocks contained directed energetic ions with extremely high ion current densities opening a new way of ignition of fusion by direct laser generation of a fusion flame in uncompressed solid fuel (Hora *et al.*, 2007). This reaction as a kind of side-on ignition was considered before as the following described hydrodynamic Chu-model but only the new experimental results of the plasma blocks provided the necessary conditions for a plane geometry interaction for fusion of deuterium-tritium.

Subsequently, it turned out surprisingly that the p-^{11}B reaction seems to be not very much more difficult with this the side-on ignition. This all seems to be feasible next by using laser pulses with dozens of petawatt power and picoseconds duration. It may lead to generation of nuclear fusion energy generating less radioactivity during the reaction, in the reactor and with the helium as end product than burning coal. This refers to the fact that burning coal produces comparable radioactivity per generated energy due to its contents of the 2 ppm uranium. The following reported results using p-^{7}Li fuel may arrive at similar negligible radioactivity generation with nuclear energy production.

Simultaneously with the thermo-kinetic interaction of lasers with plasmas at irradiation of solid targets, higher laser intensities generate highly directed low temperature plasma blocks with very high energies of ions and ion current densities exceeding 10^{10} A/cm^{2} moving mostly against the laser or into the target interior (Hora *et al.*, 2002, 2007). This block generation is caused by the nonlinear (pondermotive) force where the dielectric plasma properties are essential (Hora *et al.*, 1969, 1985, 1991) and the direction is mostly perpendicular to the plasma surface as a general hydrodynamic result (Chen *et al.*, 2005). This directivity has been confirmed also by particle in cell (PIC) computations that model is a generalized multi-particle description discovered by Wilks *et al.* (1992) where similar to the hydrodynamic result (Hora *et al.*, 1969, 1985, 1991, 2002, 2007) the target normal sheath acceleration (TNSA) was resulting (Klimo *et al.*, 2006; Dean, 2008) with modifications measured by Badziak *et al.* (2005).

For these general theoretical and numerical evaluations it is essential, that a plane geometry for the plasma surface has to be guaranteed at the necessary high laser intensities. This was never possible until the measurements by Sauerbrey (1996) using TW laser pulses of 0.5 ps duration where the observed Doppler shift fully agreed with the nonlinear force acceleration (Hora *et al.*, 2007). The result of Sauerbrey could be considered as an anomaly because any laser-plasma interaction at similar intensities never provided the conditions of the plane geometry, instead, the pre-pulses of the laser produced a plasma plume in front of the target where

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Address correspondence and reprint requests to: M. Ghoranneviss, Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran. E-mail: ghoranneviss@gmail.com the beam was shrinking to wave length diameter by relativistic self-focusing — known since 1975 (Hora (1991) section 12.2) — and where the very high laser intensity in the filament produced highly charged very energetic ions. To avoid this relativistic filamentation, Sauerbrey had to suppress any pre-pulse by a factor 10^8 (contrast ratio) for times less than dozens of ps before the main pulse arrived. The same was measured with respect to X-ray emission (Zhang *et al.*, 1998) and from the fact that fast ions had 0.5 MeV energy only (Badziak *et al.*, 1999) while relativistic self-focusing would have predicted 22 MeV. On top, the fixed number of fast ions at varying laser power led to the conclusion (Hora *et al.*, 2002) that their origin was from the skin-layer in the plasma. The generated highly directed plasma blocks had ion current densities above 10^{10} A/cm^2 all in full agreement with nonlinear force acceleration (Hora *et al.*, 2002, 2007).

These extraordinary high ion current densities produced by the laser pulses of TW or PW power and ps duration offered a come-back of the side-on laser ignition of fusion fuel at solid state density as calculated by Chu (1972), however where ps long energy flux densities above 10^8 J/cm^2 were needed for a deuterium tritium (DT) reaction. Because of these exoribitant numbers, side-on ignition was given up and the spherical compression of DT to 2000 times the solid state for laser fusion was followed up, just ready for demonstrating the historical first controlled ignition of DT to be achieved in near future with the NIF-laser (Moses *et al.*, 2006).

The observed anomaly of PW-ps laser interaction (Hora *et al.*, 2002, 2007) opened the possibility of the side-on ignition of solid DT (Chu, 1972) and the updating led to encouraging results (Ghoranneviss *et al.*, 2008; Hora *et al.*, 2008; Hora, 2009) for DT laser fusion within comparably compact reactors in the future. Another question was the use of the p-^{11}B fusion reaction producing three alpha particles only of equal energy (2.888 MeV). This was favored from the beginning because it produced less radioactivity per generated energy than burning coal due to its 2 ppm content of uranium (Deutsch *et al.*, 2008). In contrast to a spherical laser driven ignition of p-^{11}B needing a compression to 100.000 times, the solid state and low efficiencies excluding any use. The side on ignition with nonlinear force driven plasma blocks (Hora *et al.*, 2002, 2007) arrived at a very different result (Eisenbarth *et al.*, 2007; Malekynia *et al.*, 2009; Eliezer *et al.*, 1989). Working strictly only with the assumptions of Chu (1972) before further optimization (Hora *et al.*, 2008), it turned out that this scheme of laser ignition of uncompressed fuel was only about 10 times more difficult than igniting DT. This was a first step to show the possibility of controlled producing nuclear fusion energy with negligible generation of radioactivity by the reaction, within the reactor and with the helium as waste.

2. HYDRODYNAMIC CALCULATIONS

The hydrodynamic equations are used as close as possible on the same assumptions of Chu (1972) based on the DT reaction. The equations of continuity and reactions ($D + T \rightarrow \alpha + n$) may be combined to yield as equations of mass conservation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0, \tag{1}$$

and

$$\frac{\partial Y}{\partial t} + u\frac{\partial Y}{\partial x} = W, \tag{2}$$

where ρ is the mass density, u is the plasma velocity, and Y is the fraction of material burned, defined by

$$Y = (n_\alpha + n_n)/(n_D + n_T + n_\alpha + n_n).$$

W is the reaction rate function, given by

$$W = \frac{1}{2}n(1 - Y)^2\langle\sigma v\rangle.$$

It is obvious that (1) is the same as the mass conservation equation, due to the small percentage (about 0.35%) of mass transformed into energy. In the equation for Y, the n's are the particle densities, and the subscripts are for the different particle species. In the equation for W, the n stands for the total number density of the ions.

The equation of motion expressing the conservation of momentum is

$$\begin{aligned}&\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\rho^{-1}\frac{k}{m_i}\frac{\partial}{\partial x}\left[\rho(T_i + T_e)\right] + \\ &\rho^{-1}\frac{\partial}{\partial x}\left[(\mu_i + \mu_e)\frac{\partial u}{\partial x}\right]\end{aligned}, \tag{3}$$

where pressure and viscosity terms are included and the viscosity coefficients whose values are taken to be

$$\mu_{i,e} = \frac{0.406 m_{i,e}^{1/2}(kT_{i,e})^{5/2}}{e^4 \ln\Lambda},$$

where $\ln\Lambda$ is the Spitzer logarithm.

The ion and electron temperature equations are expressing the conservation of energy

$$\begin{aligned}&\frac{\partial T_i}{\partial t} + u\frac{\partial T_i}{\partial x} = -\frac{2}{3}T_i\frac{\partial u}{\partial x} + \frac{2m_i}{3k\rho}\mu_i(\frac{\partial u}{\partial x})^2 + \\ &\frac{2m_i}{3k\rho}\frac{\partial}{\partial x}(K_i\frac{\partial T_i}{\partial x}) + W_i + \frac{T_e - T_i}{\tau_{ei}}\end{aligned}, \tag{4}$$

and

$$\begin{aligned}&\frac{\partial T_e}{\partial x} + u\frac{\partial T_e}{\partial x} = -\frac{2}{3}T_e\frac{\partial u}{\partial x} + \frac{2m_i}{3k\rho}\mu_e(\frac{\partial u}{\partial x})^2 + \\ &\frac{2m_i}{3k\rho}\frac{\partial}{\partial x}(K_e\frac{\partial T_e}{\partial x}) + W_e + \frac{T_i - T_e}{\tau_{ei}} - A\rho T_e^{1/2}\end{aligned}, \tag{5}$$

were included on the right-hand side are the pressure, viscosity, conductivity, thermonuclear energy generation, equilibration terms, and energy transfer terms W_1 and W_2 following Chu (1972). The last term on the right-hand side of (6) is the bremsstrahlung term.

For the following reported computations the bremsstrahlung is based on the electron temperature T_e working with Eq. (15) of Chu (1972) with the maximum at $x = 0$, thus,

$$W_i + W_e = A\rho T_e^{1/2} + \frac{8}{9}\left(k/m_i\right)\left(1/aT_e^{1/2}\right) + \frac{2}{9}\left(T_e/t\right). \tag{6}$$

The α particles are assumed to deposit their energy in the plasma. They have a mean free path for plasma of solid state density DT was used in the initial calculations of Chu (1972, Eq. (7)) following the Winterberg approximation of the binary collisions from the Bethe-Bloch theory. This theory is for low density plasmas only where the stopping of energetic ions by electrons is described by binary interactions. For high density plasmas the stopping is determined by collective effects which results in drastically different stopping lengths as elaborated before (Hora, 2009). This case for the collective effect was then used in the new calculations for DT as well as for p-11B (Hora, 2009) and has been used correctly for our computations. Only exceptionally, we used the (pessimistic) binary collision case for p-7Li for showing the difference to the DT case of Chu (1972).

For the calculation of the collective effect we added a term to the right hand of Eq. (6) Thus

$$W_i + W_e = A\rho T_e^{1/2} + \frac{8}{9}\left(k/m_i\right)\left(1/aT_e^{1/2}\right) + \frac{2}{9}\left(T_e/t\right) + P. \tag{7}$$

Where P is the thermonuclear heating rate per unit time obtained from the burn rate and the fractional alpha particle deposition:

$$P = \rho\phi E_\alpha f, \tag{8}$$

$$\phi = \frac{dW}{dt} = \frac{d}{dt}\left(\frac{1}{2}n(1-Y)^2\langle\sigma v\rangle\right), \tag{9}$$

where the energy of the alpha particles is used and f is the fraction of alpha particle energy absorbed by electrons or ions, given by

$$f_i = (1 + \frac{32}{T_e})^{-1} \quad \text{and} \quad f_e = 1 - f_i. \tag{10}$$

In the equations after (6), the temperatures of the electrons and of the ions were used to be equal T as used in Eq. (9) for the following numerical evaluations.

Figure 1 reproduces the results of Chu (1972) for the temperature T within the generated fusion flame in the irradiated solid state DT target depending on time where the most characteristic case is for the ignition energy flux density $E^* = 4.3 \times 10^{15}$ erg/cm^2 $= 4.3 \times 10^8$ J/cm^2 and where the curve merges into a constant temperature T on time. This E^* is then the ignition threshold E_t^* as explained in more details by Chu (1972) in full agreement with Bobin (1974).

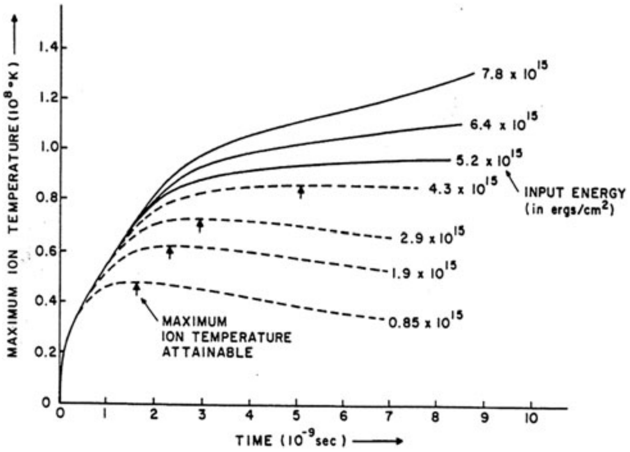

Fig. 1. Charcteristics of the dependence of the temperature T on time t for parameters E^* of energy flux density in ergs/cm^2 for ignition of fusion at solid state DT reproduced from Figure 2 of Chu (1972).

These results were fully reproduced (Ghoranneviss *et al.*, 2008) by a repetition of the computation of Chu (1972) for DT. Using the fusion cross sections for p-^{11}B arrived at the results reported before (Eisenbarth *et al.*, 2007; Malekynia *et al.*, 2009; Eliezer *et al.*, 1989).

3. RESULTS FOR THE P-^{7}LI REACTION

It was then interesting to check another candidate for this kind of safe, low cost and comparably clean nuclear power generation from the reaction of p-^{7}Li fuel. The fusion reaction rates $<\sigma v(T)>$ with the velocity averaged reaction cross sections depending on a Maxwellian temperature T

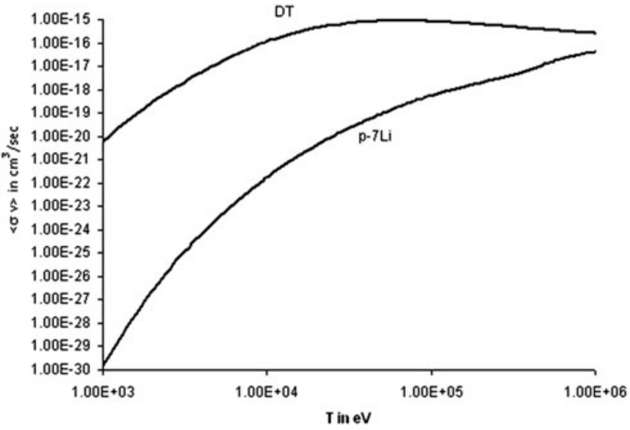

Fig. 2. Fusion reaction rates for DT and p-^{7}Li depending on the temperatures T used in the computations.

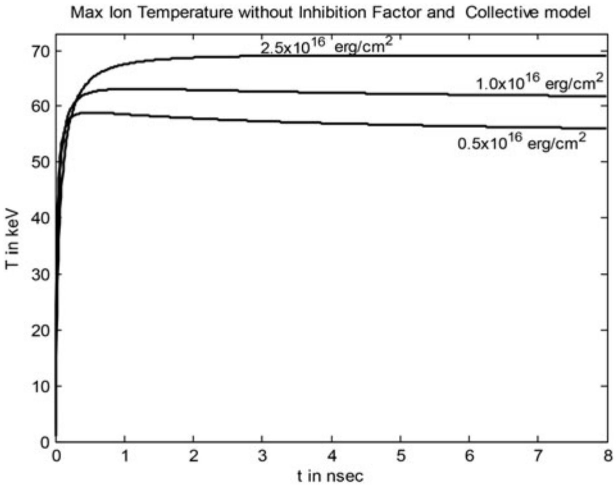

Fig. 3. Characteristics of the side-on ignition of solid state p-^{7}Li with the dependence of the temperature T of the ignition front on time t for various energy flux density of incident radiation of about ps long pulses E^* (units are the same as in Figure 1 (Chu, 1972) for comparison). The threshold for ignition is given where E^* arrives at a constant temperature at later times.

are updated values shown in Figure 2. For best comparison with the results of Chu, for DT, Figure 1, the same dimensions are used. The results for p-^{7}Li under the simplified and pessimistic conditions of Chu are reported following the analog plots of Figure 3. We derive that the threshold for the side-on ignition for the energy-flux density E^* with an ignition temperature T_{ign} is given where the curve in Figure 3 for a long time of interaction is not longer decaying but merging into a constant value

$$E^* = 2.5 \times 10^9\,\mathrm{J/cm^2},\ \mathrm{T_{ign}} = 69\,\mathrm{keV}, \tag{11}$$

where again the necessary value of E^* is within the range of 10 times higher difficulties than for DT that was estimated to be reached with few dozens of PW-ps laser pulses very close to the case of p-^{11}B (Hora *et al.*, 2007; Hora, 2009; Eisenbarth *et al.*, 2007; Malekynia *et al.*, 2009; Eliezer *et al.*, 1989). As in the case of DT of Chu (1972), for higher energy flux densities E than E^*, the plots are further increasing on time T as an expression of ignition.

It can be concluded that this result of not too much higher difficulty for the clean fusion energy generation than for DT fuel can be stated with certainty. This does not depend on minor modifications and corrections from further studies of numerous details to be gained in further studies. One modification may be due to the fact 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 (Chu, 1972; Hora, 2009; Malekynia *et al.*, 2009). However, this emission was based on thermal equilibrium functions $<\sigma v>$ with the fusion cross sections σ averaged over a Boltzmann distribution of the electron velocity v. The side-on ignition is a process in a shock front with energy production from the ions and the generated alpha particles. It may well be that the Boltzmann distribution is strongly disturbed and only details with the PIC method of Wilks *et al.* (1992) and followers (Sauerbrey, 1996; Roth *et al.*, 2005) or what was gained from the “peripheral ignition” (Winterberg, 2008) may lead to more detailed evaluations apart from several more parameters to be studied. A distinguishing is necessary between the double layer processes (Hora, (1991) Sections 8.8; 8.9; 10.7; 10.8) defined by internal electric fields in plasmas known form the genuine two-fluid computations (Hora *et al.*, 1984; Evans, 2008) determining the TNSA (Klimo *et al.*, 2006; Wilks *et al.*, 1992; Dean, 2008; Badziak *et al.*, 2005) and between physically different skin-layer mechanisms (Hora *et al.*, 2002, 2007; Badziak *et al.*, 2005) which are optically determined by dielectrically increased blocks (Hora, 1991, section 10.5) or skin depths (Hora, 2007b).

Figure 3 reports the results with the same simplified assumption of Chu (1972) for DT for comparison. We have studied the change of the results when using the collective stopping power in contrast to the usually used binary collision stopping of the Bethe-Bloch theory. In contrast to the cases with DT with a strong dependence on the stopping power model (Hora *et al.*, 2008) with changes of the temperature of the ignition threshold by few keV, a similar difference for p-^{7}Li is again by a few keV but this is comparably small in view the rather high ignition temperature of 69 keV, Eq. (11). The difference of the binary and the collective stopping was elaborated before (Hora *et al.*, 2008) in view of the usually preferred Bethe-Bloch theory in contrast to the Denis Gabor collective model which was elaborated at nearly the same time in a project at the University of Greifswald (Gabor, 1933) and re-formulated later (Gabor, 1952). It should be mentioned that the experiments with the stopping of 2 MeV electron beams in deuterated polyethylene by few mm diameter beams of 0.5 MA electron currents (Kerns *et al.*, 1972) resulted in the extremely short stopping length of 3 mm. This could be immediately reproduced by the collective stopping theory (Bagge *et al.*, 1974) for the similar high plasma densities considered here for the side-on block ignition for fusion. Moreover, for more reading, review about acceleration of plasma by nonlinear forces from picoseond laser pulses and block generated fusion flame in uncompressed fuel, Ultrahigh acceleration of plasma by picosecond terawatt laser pulses for fast ignition of fusion and Relativistic acceleration of micro-foils with prospects for fast ignition were elaborated in (Hora *et al.*, 2011; Lalousis *et al.*, 2012; Eliezer, 2012), respectively.

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