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Time and Distance Dependence of Protons Energy Loss for Laser (pw-ps) Fusion Driven Ion Acceleration

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Abstract**—**The anomalous generation of plasma blocks by interaction of petawatt-picosecond laser pulses permits side-on ignition of uncompressed solid fusion fuel following an improved application of the hydrodynamic Chu-model for deuterium-tritium. The new possibility of side-on laser ignition depends on accelerated ions and produced ions beams of high energy particles by the nonlinear ponderomotive force of the laser pulse in the plasma block, a re-evaluation of the early hydrodynamic analysis for ignition of inertial fusion by including inhibition factor, collective effect of stopping power of alpha particles and the energy loss rate reabsorption to plasma by the protons of plasma blocks being reduced by about a factor 40.

Keywords**—**Block ignition, Charged particles, Reabsorption**,** Skin layer ponderomotive acceleration.

I. INTRODUCTION

RECENT laser-fusion researches by PW (pettawat) lasers depend on accelerating of ions. The interaction of such a laser pulse with any target lead to the production of highly energetic ions. The nonlinear ponderomotive force of the laser pulse in the plasma can accelerate ions and produce beams of high energy particles. Two kinds of schemes are used for laser driven generation of ion beams, Target normal sheath acceleration (TNSA) where maximum proton energies of about tens of MeV have been observed and skin layer ponderomotive acceleration (SLPA) with maximum energy of ions about 100 keV [1]. Furthermore the stopping power of created alpha particles in fusion reactions is important.

Therefore the rate of energy loss to plasma by energetic particles is interest for thermonuclear researches. The mean energy loss per collision is determined by the Coulomb interaction given by Spitzer and Chandrasekhar. A treatment of a fast particle involves the solution of Fukker-Planck equation. This requires numerical computation of Kranzer [14] including quantum-electrodynamic corrections [17].

An interesting result - explained by Butler and Buckingham - determined the time dependence of the mean energy loss in plasma, where for the region of higher velocity of the energetic particle v than the thermal electron velocity u, the predominant energy loss is due to electrons [4].

The usual model for the treatment of the stopping power follows the Bethe-Bloch theory with several modifications by further authors as reviewed by Stepanek [19] where binary collisions between the alphas, protons or other charged particles from nuclear reactions with electrons are considered. The binary interaction results at the stopping length given by the Winterberg approximation [6].

After volume ignition was discovered [9] it was first important to see the basic confirmation of this mechanism [12]-[15] and it could be ignored that the use of the collective effect [7] arrived at two to three times higher nuclear fusion gains [9] than the binary stopping power [12]-[15]. The experiments by Kerns et al [13] 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 [2]. As an example how differences up to a factor of about three are reached, some preliminary first results from volume ignition of hydrogen-boron (11) fusion reactions by Malekynia were shown [16].

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II. TIME DEEPENDENCE OF MEAN ENERGY LOSS IN A PLASMA

The solution is begun when a test positive particle of mass M and charge Ze with v velocity in the laboratory system, colliding with a particle of mass m and charge ze with w velocity. If we assume a Maxwellian distribution for the particles of plasma with thermal speed of w_t , the time dependence of mean energy loss is obtained

$$\frac{dE}{dt} = -\frac{8\sqrt{\pi}}{m}\frac{(Zze^2)^2}{w_t}F(v/w_t)\ln\Lambda \qquad (1)$$

Where $F(v/w_t)$ is given according to (8) in [4], and $\ln\Lambda$ is the usual Spitzer logarithm. One explains is interest when $v > w_t$ we obtain

$$F(v/w_t) = \frac{w_t\sqrt{\pi}}{2v} \qquad (2)$$

Then the time dependence of mean energy loss determined

$$\frac{dE}{dt} = -\frac{4\pi}{m}\frac{(Zze^2)^2}{v}\ln\Lambda \qquad (3)$$

Where $E = \frac{1}{2}Mv^2 = \frac{3}{4}mw_t{}^2 = \frac{3}{2}kT$ and T is the temperature of the plasma particles. In Fig.1 the values of $\frac{dE}{dt}$ for alpha particle computed using the exact solution of binary collision theory and the values obtained by Perkins are plotted in [19]. Whereas for the temperatures 0.1 keV and 10 keV, good agreement is achieved.

Hora and Ray have developed a collective interaction model for the energy loss rate [9]. Ray and Hora have derived for the time dependence of mean energy loss rate:

$$\frac{dE}{dt} = -n\frac{\pi(e^2Zz)^2}{m}\sqrt{\frac{2M}{E}}\,ln\left(\frac{1}{\beta}\right)^2 \qquad (4)$$

Where $\beta = \frac{e^2Z}{mv^2\,\lambda_d}$

It is interest to note a 3.2 MeV proton (say from laser driven acceleration or a fusion reaction) gives its energy to the D-T plasma, if the temperature of plasma is 10^8 Kelvin degree we have $\frac{v}{w_i} = 30$, and $\frac{v}{w_e} = 0.4$. Thus a large fraction of the energy of such proton is converted directly to plasma electrons energies.

III. Distance Dependence of Mean Energy Loss in a Plasma For The Fast Charged Particles

The usual binary interaction results at the stopping length RBB given by the Winterberg approximation used by Lackner [15] for the result of the Bethe-Bloch theory is valid for temperatures T above 0.1 keV

$$R_{BB} \;\propto T^{\frac{3}{2}} \qquad (5)$$

In order to considering of interaction of charged particle in plasma according to collective model we use two-body collisions, therefore the energy loss of the charged particle is equal with the energy transferred to electrons

$$\Delta E = \frac{{P_e}^2}{2m_e} = \frac{2Z^2e^4}{{m_e}^2b^2v^2} \qquad (6)$$

The number of electrons between impact parameter range b, b+db and per path dx is $2\pi n_e b(db)$ dx, where n_e is the electron density. Thus, the total energy loss to the electrons per path dx is

$$\delta E = -4\pi\frac{n_eZ^2e^4}{m_eb^2v^2}bdbdx \qquad (7)$$

$$-\frac{dE}{dx} = 4\pi\frac{n_eZ^2e^4}{m_ev^2}ln\left(\frac{b_{max}}{b_{min}}\right) \qquad (8)$$

E is the energy of heavy particle; ne is the plasma electron density and $b_{max} = \lambda_d$, $b_{min} = \frac{Ze^2}{m_ev^2}$ are the maximum and minimum value of the impact parameters.

IV. New Aspect For Including Energy Loss Rate For Inertial Confinement Fusion

It should be appropriate we consider to energy loss rate as E(x,t) function therefore we can write

$$\delta E = \frac{\partial E}{\partial x}dx + \frac{\partial E}{\partial t}dt \qquad (9)$$

We include this energy loss rate reabsorption to plasma because of high density in inertial confinement fusion. Equations (4) and (8) are for one alpha particle, thus the total energy loss rate of reabsorption to plasma by the whole of alpha particles created in D-T reaction is

$$\delta E_{total} = \frac{n^2}{4} < \sigma v > \delta t \times \delta V \times \delta E \qquad (10)$$

Where $\frac{n^2}{4} < \sigma v >$ is the reaction rate in time and volume, and $< \sigma v >$ is the cross sections of fusion reaction.

Equation (10) can be used for volume ignition or block ignition methods. 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 [9].

It should be mentioned that the Gabor theory [7] 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 needs some closer consideration in view of results of volume ignition of spherically compressed pellets for fusion energy. The stopping lengths of both theories are not very much different for plasma temperatures up to about 100 eV [19].

After block ignition opens the possibility of ignition of uncompressed solid DT fuel driven by PW-PS laser pulses. It is a crucial problem that for the mentioned kind of ignition of DT with solid state density, the threshold for the necessary energy flux density E_t* is unfortunately very high [3]-[6] based on a hydrodynamic analysis. Using the particle interpenetration at interaction of an energetic plasma block beyond hydrodynamic models, the threshold may be reduced by a factor 20 [11]. The numerical evaluations with a reduction by a factor 40 reported here are based on the development of the temperature depending on the time t in order to compare the ignition condition with the results of Chu [6].

The here presented Fig. 1 shows that ignition happens at E* = 4.3×10^8 J/ cm^2 for the case solid line as seen from the time dependence of the curve continuing to be constant on time. For higher E* the curves for the temperature are still increasing on time. The dashed line is a much faster increase with the time for the ignited case by including of (10).

For a number of special cases the final evaluation can be seen in Fig. 2. It shows the development of the alpha particle energy reabsorb to plasma for the unignited case with the time t for the different E* values. In the threshold ignition E* = 4.3×10^{15} erg/ cm^2 and higher E* values for the ignited case nearly the whole of alpha particle energy come back to plasma and for the lower values nearly more than half of alpha particle energy reabsorb to plasma by using the (10) according to collective effect.

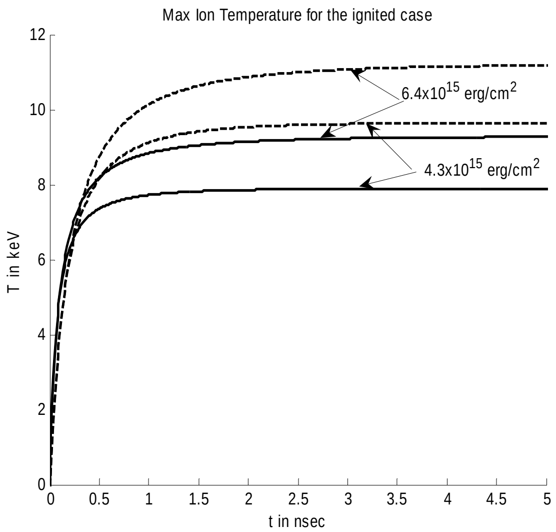

Fig. 1 Side-on ignition characteristics following Chu [6] for laser ignition of solid state DT by nonlinear force driven plasma blocks. Solid set of curves to reproduce the results of Chu, dashed set with including of the energy loss rate reabsorption to plasma by the alpha particles according to (10).

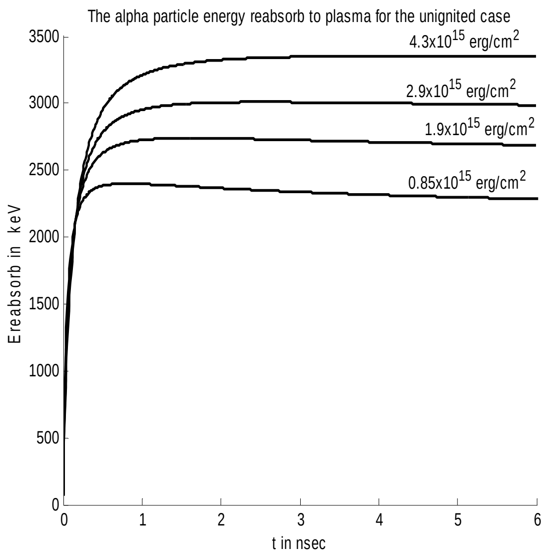

Fig. 2 The energy loss rate reabsorption to plasma by the alpha particles dependence on time in fusion plasma of solid state density with collisions with the electron collective in a Debye sphere by using the (10)

Next step is the including of impacting of fast ions with solid state density of D-T fuel. The plasma block ignition by skin layer ponderomotive acceleration (SLPA) is studied with the impacting of plasma block with D-T fuel lead in inhibition factor [8]. Using the collective stopping power alpha particle interpenetration at interaction of an energetic plasma block beyond hydrodynamic models by inhibition factor mechanism is developed in [11].

Using the particle interpenetration at interaction of energetic ions in plasma block with solid state density fuel is remarkable. The laser pulse in the plasma can accelerate plasma block and produce block of high energy particles.

Skin layer ponderomotive acceleration (SLPA) with maximum energy of ions about 100 keV can uses for developing of fusion reactors see Fig.3 of [1].With including (9) for 100 keV protons when the plasma block with density of $N_i = 10^{21} cm^{-3}$ for D-T fuel impact with solid state target [10], the total energy loss rate reabsorb to plasma by the whole of protons of plasma block can be written

$$\delta E_{total} = N_i \times \delta V \times \delta E \qquad (11)$$

Where δE is for protons according to (9), new series of computations describes in Fig. 3 with including (11). The threshold energy found in this case is E* $=1.0\times10^{7}$ J/ cm^2 that the whole cases are used (inhibition factor, collective effect of stopping power of alpha particles and the energy loss rate reabsorb to plasma by the protons of plasma block).

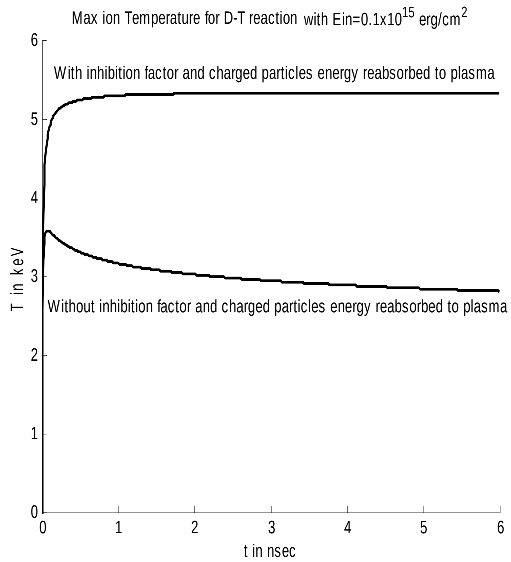

Fig. 3 Result as in Fig. 1 showing threshold ignition of solid deuterium tritium with inhibition factor, the collective effect and the energy loss rate reabsorbtion to plasma by the protons of plasma block being reduced by about a factor 40 to E* $=1.0\times10^{7}$ J/ cm^2.

V. Conclusion

We see that the values E* = 4.3×108 J/cm2 of [6] are now appearing at the lower value E* =1.0×107 J/ cm2. The result is that the ignition energy flux density E* was reduced by the inhibition factor, the collective effect and the energy loss rate reabsorb to plasma by the protons of plasma block compared with the earlier values of [6] without inhibition which was not known then. The result is then from the hydrodynamic analysis that the threshold of ignition for the energy flux density E* is reduced by a factor close to 40 due to the mentioned effects. Results showing ignition of solid deuterium tritium with the above effects can be use for H-11B and He3-He3 at future work.

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