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Twenty times lower ignition threshold for laser driven fusion using collective effects and the inhibition factor

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Hydrodynamic analysis for ignition of inertial fusion by Chu [Phys. Fluids **15**, 413 (1972)] arrived at extremely high thresholds of a minimum energy flux density E^* at 4×10^8 J/cm^2 which could be provided, e.g., by spark ignition. In view of alternative schemes of fast ignition, a re-evaluation of the early analysis including later discovered collective stopping power and the inhibition factor results in a 20 times lowering of the threshold for E^*. *© 2008 American Institute of Physics.* [DOI: 10.1063/1.2955839]

In order to produce a fusion flame by an incident radiation flux density E^* in deuterium tritium of higher than solid-state density, hydrodynamic calculations arrived at necessary extremely high energy flux densities, e.g., at a threshold of $E_t^*=4\times 10^8$ J/cm^2 for solid density deuterium tritium (DT).[1,2] One way to reach these conditions was the scheme of spark igntion[3] where it was clarified from exceedingly detailed numerical studies, that a spherically irradiated DT plasma had to have an about 7 keV hot core of modest density for producing a fusion flame into an outer DT shell of low temperature and very high compression for reaching gains of 200 more fusion energy than irradiated laser energy. The reaction in the core follows volume ignition and resulted in a value above E_t^*.[4]

In view of later developments of fast ignition[5] and further advanced modifications by block ignition,[6,7] re-examination of the early hydrodynamic computations was indicated in view of later discovered phenomena. One of them is the inhibition factor E^* for reduction of thermal conduction and the other is the effect reducing stopping lengths of the generated alphas in the fusion plasma due to the collective effects. The following hydrodynamic theory is rather limited and does not include the interpenetration effects of particles from hot into cold plasmas[8] which may be arriving at different results by using the particle in cell (PIC) techniques[9] as applied to this problem, but the question about the collision processes and the stopping lengths may still not be finalized for the present results.

In order to arrive at the best possible understanding how the effects observed since 1972 led to differences to the earlier results, the hydrodynamic equations are as close as possible following Chu[1] with appropriate modifications. The change due to the inhibition factor F^* for reduced thermal conduction in the interfaces between the hot and cold plasmas were discussed in detail before Ref. 10, where F^* was discovered experimentally and an explanation by electric double layers seemed to be sufficient while the reduction of thermal conduction by the spontaneous magnetic fields in the laser produced plasmas seemed to be of minor influence. The following results include additionally the collective effects for the stopping length of the DT fusion produced alphas. In contrast to the binary collisions of the alphas with electrons, Gabor[11] concluded a stronger collective interaction with the whole electron cloud in a Debye sphere. An experiment for very intense 2 MeV electrons[12] could be explained completely by the collective effect.[13] The drastic difference for the stoping length for plasma temperatures above 100 eV, for binary collisions used by Chu following the Winterberg approximation [see Eq. (7) of Ref. 1] for the stopping length R_{BB} of the binary Bethe–Bloch theory

$$R_{\mathrm{BB}} \propto T^{3/2} \tag{1}$$

was shown in Fig. 6 of Ref. 14, where the collective interaction[11,15] resulted in a very weak dependence of the range R on the temperature T with very much shorter stopping lengths for solid-state density DT

$$R = 0.01 - 1.7002 \times 10^{-4} T \text{ cm} \quad (\text{temperature } T \text{ in keV}). \tag{2}$$

To be as close as possible to the analysis of Chu,[1] the following hydrodynamic equations are used. The equations of continuity and reactions $(D+T\rightarrow \alpha+n)$ may be combined to yield as equations of mass conservation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0 \tag{3}$$

and

$$\frac{\partial Y}{\partial t} + u\frac{\partial Y}{\partial x} = W, \tag{4}$$

where ρ is the mass density, u is the mass 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

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

It is obvious that Eq. (3) is the same as the mass conservation equation, due to the small percentage ($\sim 0.35\%$) of the 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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\rho^{-1}\frac{k}{m_i}\frac{\partial}{\partial x}[\rho(T_i+T_e)]+\rho^{-1}\frac{\partial}{\partial x}\left[(\mu_i+\mu_e)\frac{\partial u}{\partial x}\right],\qquad(5)$$

in which the pressure and viscosity terms are included. $\mu_{i,e}$ are 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 usual Spitzer logarithm.

The ion and electron temperature equations expressing the conservation of energies

$$\frac{\partial T_i}{\partial t}+u\frac{\partial T_i}{\partial x}=-\frac{2}{3}T_i\frac{\partial u}{\partial x}+\frac{2m_i}{3k\rho}\mu_i\left(\frac{\partial u}{\partial x}\right)^2+\frac{2m_i}{3k\rho}\frac{\partial}{\partial x}\left(K_i\frac{\partial T_i}{\partial x}\right)+W_i+\frac{T_e-T_i}{\tau_{ei}}\qquad(6)$$

and

$$\frac{\partial T_e}{\partial x}+u\frac{\partial T_e}{\partial x}=-\frac{2}{3}T_e\frac{\partial u}{\partial x}+\frac{2m_i}{3k\rho}\mu_e\left(\frac{\partial u}{\partial x}\right)^2+\frac{2m_i}{3k\rho}\frac{\partial}{\partial x}\left(K_e\frac{\partial T_e}{\partial x}\right)+W_e+\frac{T_i-T_e}{\tau_{ei}}-A\rho T_e^{1/2}\qquad(7)$$

were included on the right-hand side using the pressure, viscosity, conductivity, thermonuclear energy generation, equilibration terms, and energy transfer terms W_1 and W_2 following Chu.[1] The last term on the right-hand side of Eq. (7) 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[1] with the maximum at $x=0$; thus,

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

Equation (8) is a little different from Eq. (20) of Chu[1] where $T_i=T_c$ is assumed while the following computations with the collective stopping has to be for general temperatures. The α particles are assumed to deposit their energy in the plasma. They have a mean free path for solid-state density DT according to Eq. (2) for the collective effect to distinguish from Eq. (1) used by Chu.[1] For the calculation of the collective effect, a term to the right-hand side of Eq. (8) was added

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

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

$$P=\rho\phi E_\alpha f,\qquad(10)$$

$$\phi=\frac{dW}{dt}=\frac{d}{dt}\left(\tfrac{1}{2}n(1-Y)^2\langle\sigma v\rangle\right),\qquad(11)$$

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

$$f_i=\left(1+\frac{32}{T_e}\right)^{-1}\text{ and }f_e=1-f_i.\qquad(12)$$

For the equations after Eq. (8) the temperatures of the electrons and of the ions were used to be equal T as used in Eq. (2) for the following numerical evaluations.

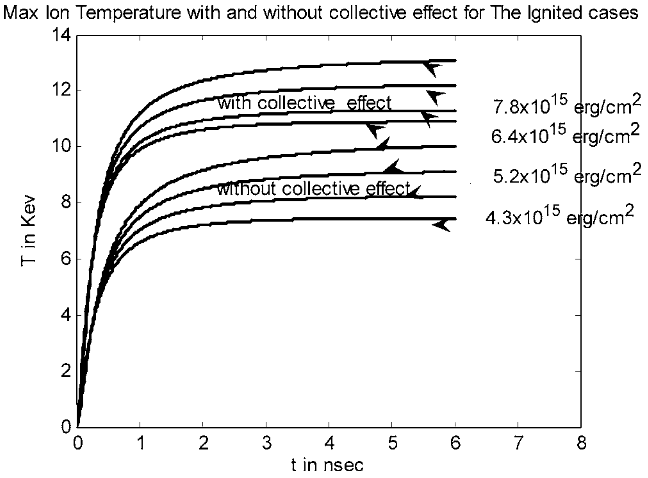

FIG. 1. Characteristics of the plasma temperature T on time t similar to Fig. 2 of Chu (Ref. 1) with the energy flux density E^* in erg/cm^2 with and without the collective effect for the stopping of the alphas from the DT reaction. Transition into constant temperature on time for 4.3×10^8 J/cm^2 corresponds to the threshold for ignition nearly identical with the computation of Chu (Ref. 1) without collective effect and all without inhibition factor.

Ignition can best seen from Fig. 2 of Chu[1] showing the temperature on time t in the irradiated plasma. The present work without the collective effect is shown in Fig. 1. At an energy flux density $E^*=4.3\times10^8$ J/cm^2, the plasma temperature T merges into a constant time dependence exactly what was the result of Chu, see Fig. 2 of Chu.[1] This E^* is the threshold E_t^* because lower values of E^* result in a decrease of T on t and higher values show an increase of T on t. Figure 1 reports also the results with the collective effect obviously resulting in higher plasma temperatures.

The calculation with the inclusion of the inhibition factor was based on experiments where E^* was measured to be between 30 and 100.[10] The theoretical value is determined by the thermal conductivity within the double layer, given by that of the ions K_i and not by that of the electrons K_e. Classical theory without magnetic fields arrives at

$$K_i=K_e(m_e/m_i)^{1/2}\qquad(13)$$

determined by the electron mass m_e and ion mass m_i. For DT the value E^* is then 67.5. Using this inhibition factor E^* in the hydrodynamic computations, the plots similar to Fig. 1 with and without collective effect are given in Fig. 2. This shows that the threshold for ignition with the collective effect and with the inhibition factor is at a value

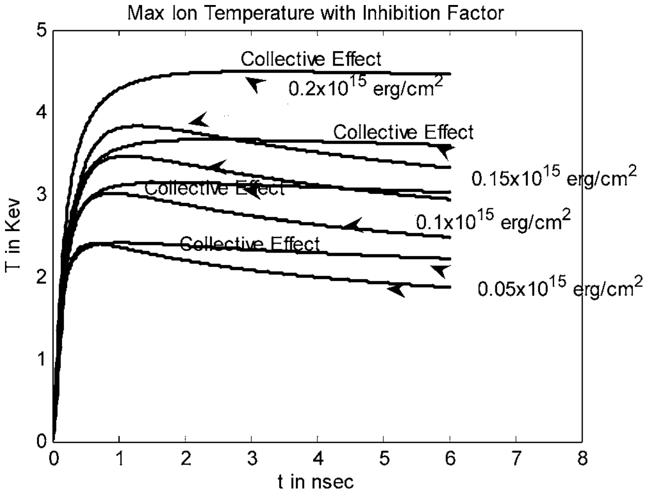

FIG. 2. Same as Fig. 1 with inhibition factor and with and without the collective effect for stopping of the alphas demonstrating ignition at 2×10^7 J/cm^2.

$$E_t^* = 2 \times 10^7 \text{ J/cm}^2. \qquad (14)$$

This is a reduction from the initial value of Chu[1] by a factor 21.5. A separate analysis without collective effects was treated in several details only with the inhibition factor.[10]

The value E^* in Eq. (14) is still extremely high, and it will be a question whether conditions of the block ignition with many petawatt-picosecond laser pulses[7] could be within realistic conditions. In view of the initially mentioned interpenetration problems,[8,9] the final decision may still be open. When the next measurements with spark ignition may be gained from experiments like that of the National Ignition Facility NIF,[16] it may be of interest whether the here reported re-evaluation of the hydrodynamic model apart from other theories based on PIC or other techniques may lead to a clarification of the processes involved.

Though the here presented results were initiated by a modification of fast ignition for laser fusion with laser pulses of picosecond duration and one dimensional plane geometry interaction,[7] the connection with nanosecond laser pulse interaction for central spark ignition[17] may be seen from Chu's[1] threshold $E^* = 4 \times 10^8$ J/cm^2. The computations for the spark ignition with the hydrodynamically equivalent physics[17] were possible with the absence of alpha-particle deposition. The re-calculation of the spark ignition[4] had shown that the energy flux density E^* from the spark for ignition of the outer low temperature and high compression mantle was not much higher than the value of Chu. It should be noted that the reaction of the spark was found to fit[4] with volume ignition,[18–20] where the alpha reheat based on the collective stopping was essential. Other measurements of reduced stopping lengths are known from research on heavy ion driven laser fusion.[21] This is the reason why the here reported change of the ignition threshold may lead also to phenomena to be explored with the next studies of spark ignition with NIF (Ref. 16) or similar experiments.

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