Modification of the Bobin-Chu Fusion Threshold for Laser Driven Block Ignition or for Spark Ignition

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Abstract. A unique anomaly at interaction of ps-TW laser pulses with targets was discovered if the pulse had a contrast ratio of 10^8 for times up to 50 ps before the main pulse arrived. This elimination of the prepulse suppressed relativistic self- focusing in contrast to all usual experiments. Highly directed plasma blocks were generated by nonlinear (ponderomotive) force acceleration of skin layers to arrive at highly directed space charge neutralized 100 keV ions with current densities above 10^{11} Amps/cm^2. For using these pulses for fusion energy thresholds E_t* flux densities of 100 MJ/cm^2 were calculated by Chu 1972. We revised and updated these calculations by taking into account later discovered phenomena as inhibition of thermal conduction and collective effects and arrived at a reduction of the threshold by a factor of more than 20. This is interesting also for spark ignition and other laser fusion schemes. For the block ignition of DT, parameters are evaluated since conditions have to be met that the DT ions in the blocks should not have higher energies than in the range of 100 keV while the mentioned threshold requires sufficiently high intensities of the laser pulse. The here reported decrease of the threshold simplifies the mentioned conditions.

1. Introduction

Chu [1] and Bobin [2] derived the threshold of the energy flux density E* for generating a fusion flame within a low temperature plasma at the impact by a short pulse of high energy density e.g. as an incident hot plasma. The threshold was found to be at a very high value with the a limit [1]

$$E^* > E_t^* = 4.5\times10^8 \text{ J/cm}^2 \quad (1)$$

This may have been a motivation to invent the spark ignition [3,4] where laser irradiation of a spherical fusion pellet is going to produce a very specific density and temperature profile. Based on very detailed properties known for laser produced fusion plasmas and from detailed computations [5], a laser pulse of ns duration and 10 MJ energy should produce 100 times more energy. The very specific profiles permitted a low-density high-temperature deuterium tritium (DT) spherical core to react by volume ignition [6-11] to produce a very high value E* at the core surface connected to a low-temperature very high density DT mantle. E* was found [11] to be close to 10^9 J/cm^2 when evaluating the known case [5] in agreement with the result of Chu, Eq. (1).

Since laser pulses of ps duration and higher than PW power are available, an ignition scheme with a 10 kJ laser pulse for producing very high intensity beams of 5 MeV electrons is considered to generate 100 MJ fusion energy by interacting with deuterium-tritium (DT) of only 12 times solid state density [12] as a modificaton of the fast ignition [13]. Extending this to a scheme with using DT ion beams instead of electrons seems to be possible [14] by using a very special anomaly observed with TW-ps laser pulses [15,16]. In this case again the condition of Eq. (1) is a hurdle which may be difficult to be overcome. Though experiments [17] confirming and elaborating details of the anomaly [14-16] resulted in E* values close to 10^6 J/cm^2 it was of interest – also in view of the mentioned questions with the spark ignition [4] – to re-consider the hydrodynamic calculations which led to the results (1) in 1972 where a number of phenomena were not at all known. It has to be realized that chemical detonation waves after having been analysed in details first by Döring [18] and von Neumann [19] are basically different to the case of thermonuclear reactions [20,21]. The following hydrodynamic treatment is not fully complete, because it is not considering the interpenetration between hot and cold plasma [22] but may better be covered by PIC [23] methods [24] possibly with a further decrease of the ignition thresholds also in spark ignition experiments [25] as for block ignition [16].

The following is considering how E_t* is changed by taking into account the inhibition factor F* which describes the experimentally discovered strong reduction of the thermal conduction between energetic plasma hitting a low temperature plasma. A further point is the reduction of the stopping length R for the fusion produced alphas in plasmas due to collective effects compared with the usually considered binary collisions of the Bethe-Bloch theory. For orientation, the next following section first is to summarize the anomalous results of TW-ps laser pulse interaction.

2. Anomaly of plasma block generation

Irradiating (TW to PW)-ps laser pulses on targets [26] usually results in extreme relativistic effects as generation of highly directed electron beams with more than 100 MeV energy, in highly charged GeV ions, in gamma bursts with subsequent photonuclear reactions and nuclear transmutations, in positron pair production, and high intensity very hard x-ray emission. In strong contrast to these usual observations, few very different anomalous measurements were reported. What was most important in these few cases, is that the laser pulses with TW and higher power could be prepared in a most exceptionally clean way to have a suppression of pre-pulses by a factor 10^8 (contrast ratio) or higher for times a few dozens of ps before the main pulse is hitting the target. These very clean laser pulses were most exceptional and especially possible by using the Schäfer-Szatmari-method with excimer lasers by Sauerbrey [27] or with chirped pulse amplification (CPA) using titanium-sapphire lasers by Zhang et al. [28], and by Badziak et al. [29] using neodymium glass lasers.

These exceptional conditions could be understood from the results of very detailed one-dimensional computations of laser-plasma interaction with dominating nonlinear (ponderomotive) forces [14-16]. It was shown, [30, Fig. 3], that irradiation of a deuterium plasma block of specially selected initial density (bi-Rayleigh profile) with a neodymium glass laser intensity of 10^{18} W/cm^2 resulted within 1.5 ps in a thick plasma block moving against the laser light with velocities above 10^9 cm/s and another similar block moving with the laser direction into the plasma interior. However, such a generation of plasma blocks was never observed because in all experiments, a minor pre-pulse produced a plasma in front of the target where the laser beam was shrinking to about one wavelength diameter with extremely high intensities due to relativistic or ponderomotive self-focusing [31].

The acceleration was then dominated by the nonlinear force f_{NL} given by the time averaged values of the amplitudes of the electric field **E** and the magnetic field **H** of the laser in this simplified geometry at perpendicular incidences in the x-direction as [32]

$$f_{NL} = (\mathbf{n}^2-1)(\partial/\partial x)(\mathbf{E}^2/16\pi) = -(\partial/\partial x)[(\mathbf{E}^2 + \mathbf{H}^2))/(8\pi)] \qquad (2)$$

where **n** is the complex index of refraction in the plasma. The first expression reminds of the ponderomotive forces derived by Kelvin for electrostatics before Maxwell's theory while the second expression represents the force density as gradient of the energy density given generally by Maxwell's stress tensor. Thanks to the clean laser pulses of the Schäfer-Szatmari method, *it was for the first time ever* that Sauerbrey [27] could avoid the self-focusing and measure the generated plane plasma block moving against the laser light with an acceleration derived from Doppler shift. This was very accurately reproduced by the nonlinear force theory [16, section II.4].

The second crucial experiment with the anomaly were performed with *clean* laser pulses of about 30 wavelength diameter by Zhang et al. [28] irradiating the target with 300 fs laser pulses. There was only a modest x-ray emission, not the usually very intense hard x-rays. When taking out a weak pulse and pre-irradiate this at times t* few ps before the main pulse, the x-rays were unchanged. But as soon as t* was increased to 70 ps, the usual hard x-rays were observed. It was estimated [14] that the 70 ps were just needed to build up the plasma plume before the target which is necessary for providing relativistic self-focusing with the subsequent usual relativistic effects.

A third crucial observation was by Badziak et al [29] when irradiating copper targets with half TW very *clean* laser pulses of few ps duration. Instead of the expected and usually measured 22 MeV fast copper ions, the fast ions had only 0.5 MeV energy. Furthermore it was observed that the number of the fast ions (in difference to the slow thermal ions) was constant when varying the laser power by a factor 30. From this it could be concluded [14,15] that the acceleration was from the unchanged volume of the skin layer at the target surface where the nonlinear force led to the generation of a highly directed plane plasma block moving against the laser. This skin layer accleration by the nonlinear force, SLANF, with avoiding self-focusing was then confirmed experimentally in all details, especially from high directivity of the fast ions and the generation of a plasma block towards the plasma interior, as carefully measured when irradiating thin foils on the back side of the target [33].

Most significant was the result from the beginning [14,15] that the SLANF-generated directed space-charge neutral plasma blocks should have an ion current density of 10^{11} Amps/cm^2 as confirmed experimentally later [33]. This also led to reconsidering the scheme of direct ignition of solid state or modestly compressed DT by the plasma blocks [16] for fusion energy production similar to the scheme of Nuckolls et al [12] using very intense 5 MeV electron beams generated by 10 PW-ps laser pulses. The only difficulty for igniting solid-state density DT is that there is the need of an exorbitantly high energy flux density E* given in Eq. (1).

3. Reduction of the ignition threshold E* by transport barrier

The reduction of the thermal conductivity of the electrons by the inhibition factor F* was discovered in an empirical way from the evaluation of experiments for laser fusion. Experiments were performed with targets of different layers and the diagnostics by x-rays etc. resulted in a reduction of the thermal conduction by factor a F* = 33 [34]. Other experiments resulted in a reduction by a factor 100 [35]. Several theories tried to explain these results assuming magnetic fields, ion-acoustic turbulence or Weibel instabilities as reasons. The closest to arrive at the clear facts was that of Tan Weihan and Gu Min [36] based on the Krook equation leading to pressure effects since these are causing ambipolar fields and therefore internal electric fields.

The knowledge about the internal electric fields in inhomogeneous plasma (homogenous plasmas have a decay of any electric field like in metals within femtoseconds) arrived from the nonlinear (ponderomotive) forces, Eq. (2), though the general theory was derived from the space-charge neutral two-fluid model for the general transient case [37, section 8.6] valid for lengths larger than the Debye lengths

$$\lambda_D = \{kT/(4\pi n_e e^2)\}^{1/2} \qquad (3)$$

where T is the plasma temperature with Boltzmann's constant k, and n_e is the density and e the charge of electrons. When studying the single particle motion of the electrons in the laser field in the plasmas [37, section 8.7], the same nonlinear force was derived considering the space-charge neutral electron fluid being drifted by the gradient of the square of the laser field, Eq. (2) as a result of electrostriction. The ions follow then by electric attachment to the moving electron cloud. This could be seen in all details numerically, however only by using a genuine two-fluid model with separate electron and ion fluids and combined by a Poisson term [37, sections 8.8 and 10.7].

The same electric field spreading over of the thickness of a Debye length is at the surface of a laser produced plasma expanding into vacuum or at any interface between two plasmas with different temperature and/or density, as shown for the simplified case in Fig. 1. The electrons of the hot plasma part leave the Debye layer towards the vacuum or to the cold plasma or wall and let the ions behind in the Debye layer. Any electric conduction is then determined by the ions such that the thermal conductivity of the plasma is given by that of the ions, K_i and not by that of the electrons K_e which both are related by

$$K_i = K_e(m_e/m_i)^{1/2}\,; \qquad F^* = (m_i/m_e)^{1/2} \qquad (4)$$

Where m_e is the electron mass and m_i the ion mass (in our case the average mass of D and T ions). For our case the relating factor F* = 67 for the inhibition of thermal conduction, is well within the rather complicate experimental values of 30 [34] or 100 [35]. This inhibiton factor F* is now used for the improved hydrodynamic computation of the E* values.

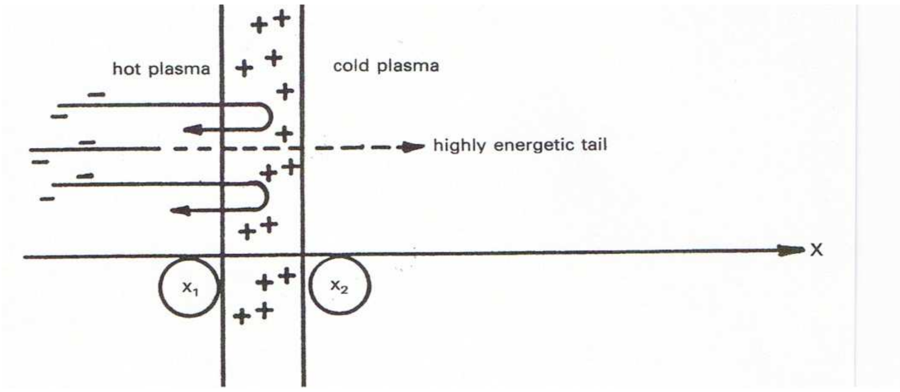

FIG. 1 Double layer at plasma surface or interface of Debye layer thickness depleted of electrons [42, p. 31].

4. Collective effect for the stopping of alpha particles

After the just discussed problem of thermal transport, the question of the transport properties for the stopping of the DT fusion produced alpha particles in plasma are important for the ignition. Chu [1972, see Eq. (7)] used the Winterberg approximation for stopping by binary collisions combining roughly all the numerical models mostly following the Bethe-Bloch theory. An comprehensive summary of these models was given by Stepanek, especially for the alphas of the DT reaction [38, see figure 6] where the Bethe-Bloch stopping length R increases as

$$R \propto T^{3/2} \qquad (5)$$

on the plasma temperature T.

A visible discrepancy appeared with the measurements by Kerns et al [39] at the Air Force Weapons Laboratory of the Kirtland Air Force Base where an electron beam with 2 MeV energy and 0.5 MA current of 2mm diameter was hitting deuterated polyethylene CD_2. The electron stopping was measured from the saturation thickness d of fusion neutrons at d = 3mm. This was very much shorter than the Bethe-Bloch theory predicted. An explanation of the experimental value d was immediately possible when Bagge's [40] collective theory was applied where the charged energetic particles interacted with the whole electron cloud in a Debye sphere and not by binary electron collisions. The discovery of this collective interaction was by Denis Gabor [41,42] confirmed by using the Fokker-Planck equation and quantum electrodynamics [43]. Another drastic difference of the stopping length in contrast to the Bethe-Bloch theory was measured in a direct way by Hoffmann et al [44].

Following a diagram by Stepanek [38, Fig. 6] the dependence of the stopping length R of alphas form DT fusion on the temperature T of a DT plasma can be approximated by

$$R = 0.01 - 1.7002\times10^{-4}\, T \quad \text{cm} \qquad (5)$$

where the temperature T is in keV. R is then nearly constant by the collective effect in contrast to the $T^{3/2}$ dependence of the stopping by binary collisions.

5. Hydrodynamic calculations

In order to see the importance of the collective effect of the stopping power in the hydrodynamic equations, first the results of Chu [1] are going to be reproduced with a minium of changes in the conditions he had used before, but with adding now the collective stopping length R and the inhibition factor F*. Details of the hydrodynamic equations were given before [45,46] using exactly the formulations as Chu [1]. For comparison, the characteristic plots are given in Fig. 2 where the fully drawn lines with an increasing plasma temperature T on time t with an input energy flux density E* showing ignition, while the dashed decreasing curves are below the ignition threshold. We see that the ignition threshold is at an input energy of $E_t^* = 4.5\times10^8$ J/cm^2, see Eq. (1).

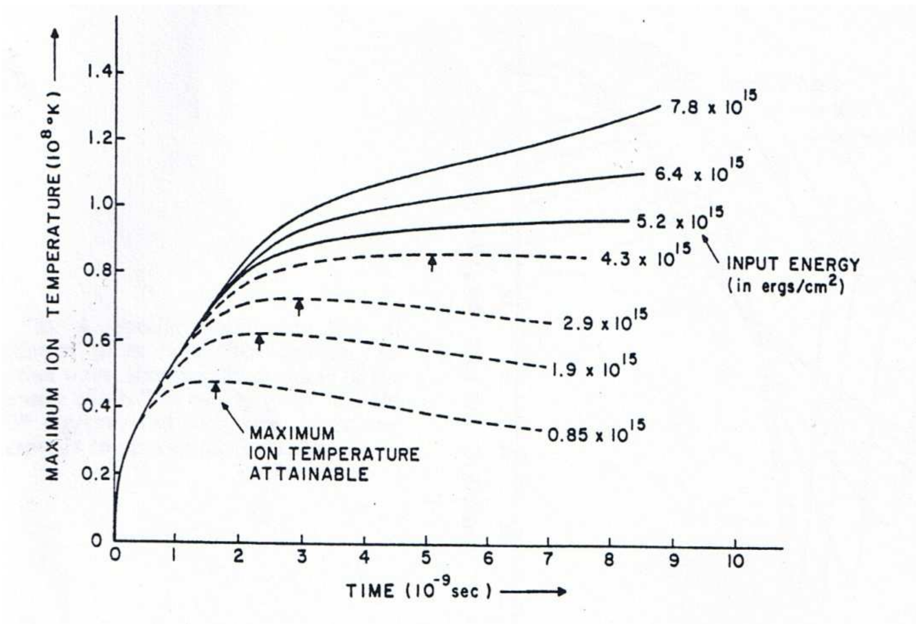

Fig. 2 Results of Chu [1] of 1972: Ion temperature T in DT of solid state density on time t at given input energy flux density E with solid lines showing ignition.*

It is to be underlined from the preceding section, that the collective effect and the inhibition were not at all known at the time of Chu's treatment. The following diagram shows the results with inclusion of the inhibition factor F* = 67 and with the collective stopping power, Eq. (5). Control runs without these inclusions arrived nearly at the same curves as shown in Fig. 2 of Chu [1] where some small deviations were with a little faster increase between 0 and 1.5 ns. The finer resolution of the plots showed some retrograde behaviour with a little faster increase of T on time t for lower values of E*. This could be qualitatively be explained [45].

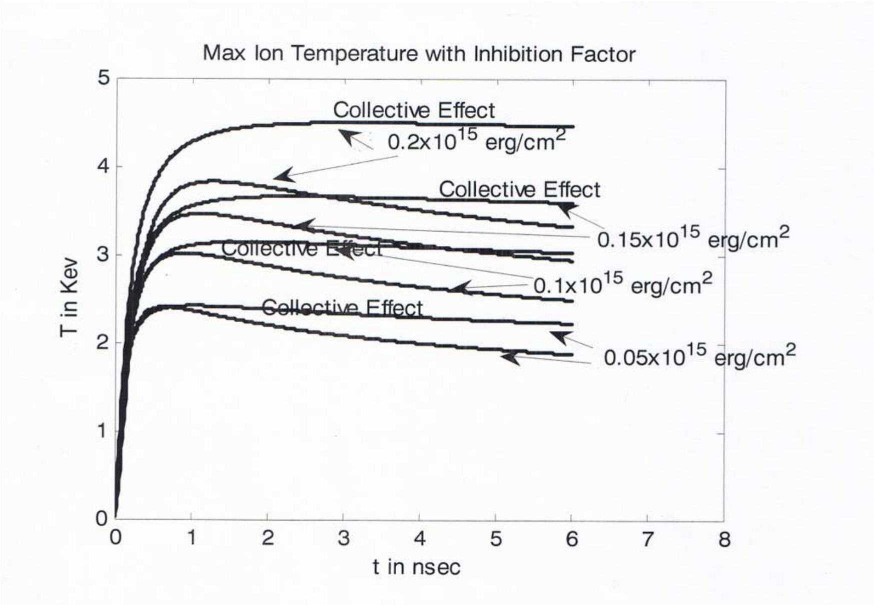

Fig. 3 Dependence of DT plasma temperature T on time t with collective effect and inhibition factor for varying parameter of input energy flux density E compared with the decaying curves with inhibition factor only.*

Fig. 3 shows the results where ignition is seen at least for $E^* = 2\text{x}10^7$ J/cm^2 or even at little lower E*. The ignition threshold E_t^* was therefore decreased by a factor of at least 22.5.

6. Conclusion

As a very preliminary estimation for an example, irradiation of a laser pulses of 10 kJ energy during 1 ps on a cross section of 10^{-2} cm^2 corresponds to an intensity of 10^{18} W/cm^2. Up to 0.5 times of the irradiated laser energy can be converted into the kinetic energy of the DT ion block, equivalent to an energy flux density of 5×10^5 J/cm^2. The thickness of the compressing block moving parallel to the direction of the laser beam is assumed to be 10 μm [47]. Conical motion of this block [16, Fig. 6] leads to a cross section of 10^{-4} cm^2 of the block of plasma with the directed energy of the DT ions of 80 keV. The block at interaction has a length of 1mm and an energy flux density of 5×10^7 J/cm^2. This just may meet the requirements for ignition of solid DT as elaborated in Section 5.

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