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High Density Particle Beams Driven by Petawatt-Picosecond Clean Laser Pulses for Fusion

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Controlled fusion reactions with ignition of uncompressed solid DT by DT ion beam was found to require light ion beam current densities of 10^{10} A/cm^2 and energy densities in the order of $E_d = 10^8$ J/cm^2. These conditions were very far beyond the available beam technologies. However the CPA laser technology has provided these beam densities. The measurements of Badziak et al with very clean – i.e. with a contrast ratio above 10^8 - TW-ps laser pulses demonstrated that relativistic self-focusing was avoided and the conditions of plane wave geometry could be applied to produce a skin layer interaction process. The experiments confirmed that the emitted ion blocks driven by the nonlinear force against and with the laser beam showed the concluded 10^{10} A/cm^2 moving within narrow angels. We report how the limit E_d may be realized such that the laser driven plasma block as a kind of light ion beam driver may induce a reaction in uncompressed solid DT where 10 kJ-ps laser pulses may produce several 10 MJ fusion energy.

1. Introduction

A new dimension for laser interaction with plasmas was opened by the recent developments of laser pulses with powers exceeding petawatts (PW=10^{15}W) with duration in the range of few picoseconds down to several femtoseconds (fs), mostly by the technique of the chirped pulse amplification of Mourou [1]. For laser driven fusion energy, these pulses were of interest for the new fast ignitor scheme [2,3] where modifications were discussed, e.g. that of Nuckolls and Wood [4] where such a laser pulse in highly compressed plasma produces a very intense 5 MeV electron beam which ignites a fusion detonation wave in DT where rather low densities of the magnitude of ten times the solid state are preferred. In this case, the PW-ps laser generates conditions of a beam fusion with the relativistic electron beam. This scheme may need the control of numerous unexpected relativistic effects while the use of NIF-like laser pulses of several MJ energy and ns duration is another well-developed option for laser fusion [5]. Another alternative for the use of PW-ps laser pulses was opened by the experiments of Badziak et al [6] which could be explained only by the special conditions that relativistic self-focusing was avoided, and a skin layer interaction [7] produced plasma blocks with ion current densities above 10^{10} A/cm^2 in the space-charge neutral plasma by a sub-relativistic interaction [8]. These ion current densities invite to reconsider the very early-discussed possibilities how a fusion flame [9] could be produced in uncompressed solid DT fuel.

2. Generation of very dense and high energy plasma blocks

Badziak et al [6] observed the TW-ps laser pulses produced ion emission, which was basically different from the usual ion generation by lasers with pulses of more than 100 ps duration [10]. Instead of producing groups of energetic ions up to 80 MeV energy with linear energetic separation on the ion number Z with the long pulses, only one group of ions appeared with the short pulses with a very narrow directivity against the laser light [8], with remarkable lower ion energies than with long pulses as known from relativistic self focusing, and with the property that the number of the energetic ions did not depend on the power of the laser pulse [6]. This all could be satisfactorily explained as a skin layer process [11] where the emitted x-radiation, the ion energy on its Z-dependence, including a reasonable dielectric swelling by a factor 3 for the nonlinear force produced block acceleration were completely consistent. The suppression of prepulses (contrast ratio of up to 10^8) to avoid relativistic self-focusing was evident in the same way as this was demonstrated by the x-ray emission from targets at similar laser irradiation and how prepulses at varying time of incidence could avoid or intentionally generate conditions of relativistic self -focusing [12].

This plane wave one-dimensional interaction was well known from detailed numerical studies with most realistic ingredients, Fig. 1, where a 1.5 ps laser pulse of 10^{18} W/cm^2 results in a swelling of the electromagnetic energy density $(\mathbf{E}^2 + \mathbf{H}^2)/8\pi$the negative gradient of which is the nonlinear (ponderomotive) force which is driving one deuterium plasma block of many wave length thickness up to 10^9 cm/s against the laser light and another block into the target.

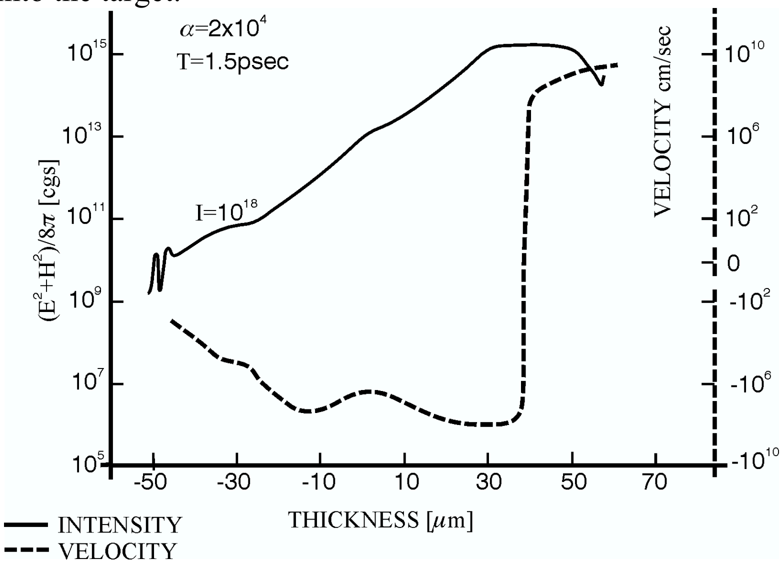

Fig. 1. Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100 eV hot and 100 μm thick bi-Rayleigh profile (Fig. 10.17 of [13]) with minimum internal reflection. The electromagnetic energy density $(\boldsymbol{E}^2+\boldsymbol{H}^2)/(8\pi)$ is shown at the same time of 1.5 ps after begin of the constant irradiation [13].

The interpretation of the skin layer mechanism for the experiments of Badziak et al [6,7] can be understood in the same way as drawn in Fig. 2 where these blocks can reach ion densities above 10^{10} A/cm^2 as measured [8,14] in both directions.

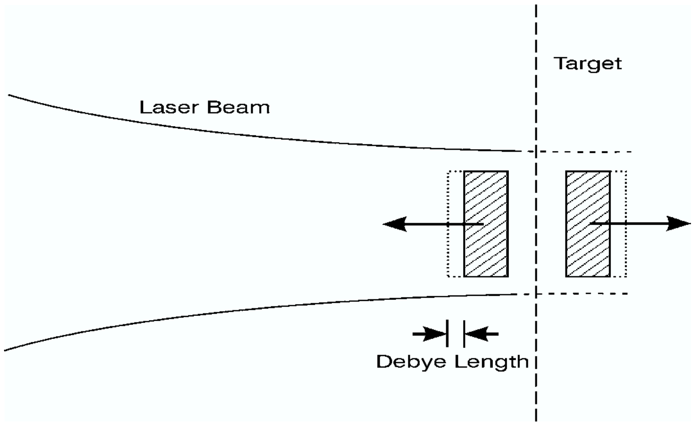

Fig. 2. Scheme of skin depth laser interaction where the non-linear force accelerates a plasma block against the laser light and another block towards the target interior. In front of the blocks are electron clouds of the thickness of the effective Debye lengths of less than 500 nm [13].

3. Application to laser fusion

The just reported result of plasma blocks with ion current densities above 10^{10} A/cm^2 for ion energies above 80 keV up to higher values permit an application to beam fusion with uncompressed solid DT fuel. The ion beam current density j had to be above the threshold [9]

$$J > j^* = 10^{10} \text{ A/cm}^2 \qquad (1)$$

and the energy density the for generating a reaction front (flame propagation) into uncompressed solid DT was derived theoretically [9] to be above the threshold

$$E^* = 4\text{x}10^8 \text{ J/cm}^2 \qquad (2)$$

Even more pessimistic higher thresholds E* were considered which however may be upper bonds only as long the very extensive details for the derivation of the threshold (2) are not found to be incorrect. However the inclusion of interpenetration processes [15] may lead to lower thresholds as $E^*_1 = 2\text{x}10^7$ J/cm^2. From this result it was concluded that the compressing block may be used as requested for light ion beam fusion for a power station. A 10 kJ laser pulse could then produce 10 MJ or more fusion energy where the exclusive use for the controlled reaction was confirmed by a declassification procedure by the authorities involved. To what extend the conditions 2 can be fulfilled for any value E*, a laser pulse length t_L, for the desired oscillation energy ε_{osc} at a given Swelling S [13] defined the necessary laser wave length (the shorter the better), Fig. 3

$$\lambda(\varepsilon_{\tau\rho\alpha\nu\sigma}, E^*, t_{L,} S) = [t_L I^*_{rel}/(3SE^*)]^{1/2} \{[(\varepsilon_{trans}/m_o c^2) + 1]^2 - 1\}^{1/2} \qquad (3)$$

Using as a special case $t_L = 3$ps, $E^* = 2\text{x}10^7$ J/cm^2, $\varepsilon_{trans} = 80$ keV for the DT reaction, we arrive at $= 0.516/S^{1/2}$ µm. For more pessimistic higher E* values, very short laser wavelengths (harmonics of excimer lasers) could well fulfil the conditions of igniting solid DT fuel, however, more detailed studies of E* in view of [13] the quantum modification of collisions, double layer reduction of thermal conduction and the interpenetration point into the direction of lower E* values. First steps for these studies were reported before [16].

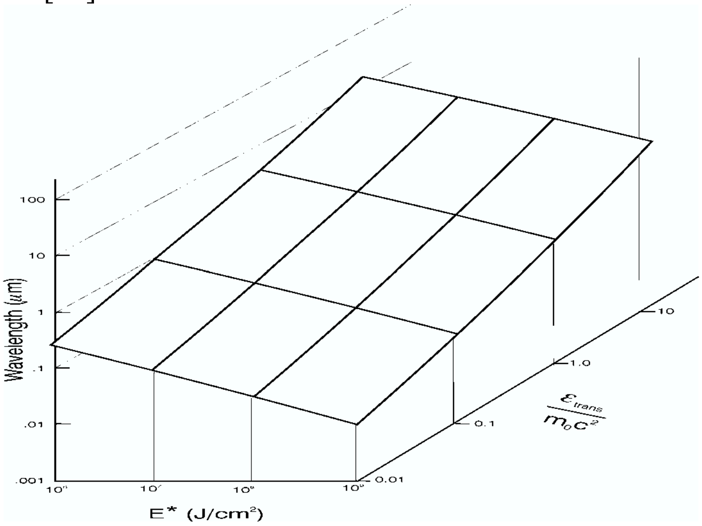

Fig. 3. Relation between the laser wave length the aimed ion energy ε_{trans} in multiples of $m_o c^2$ and the necessary energy flux density for ignition of uncompressed DT following Eq. (3) for S = 1 and a laser pulse length of 3 ps.

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