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Nonlinear Force Laser Driven Plasma Blocks for Fast Ignition

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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 [1] in full agreement with the experiments with the consistence of a dielectric swelling of 3.5. 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 cones [2] in contrast to all the cases with relativistic self-focusing. We report how the limit of 10^8 J/cm^2 energy density can be lowered by up to a factor 50 if collective effects, anomalous resistivity and particle interpenetration are included such that the laser driven plasma block as a kind of light ion beam driver may induce a reaction solid state DT where 10 kJ-ps laser pulses may produce 100 MJ fusion energy. After the use for controlled fusion was clarified and any other use was excluded by a declassification procedure, this permitted first publications [3]. As a consequence of this, we report about the possibilities for a fast ignitor-like fusion power scheme where solid DT fuel may be used without compression.

A significantly new and unexpected result – for which we present here a further confirmation by numerical studies closer to the experimental conditions – is the generation of the plasma blocks based on the observation of the very anomalous maximum ion energies at irradiation with TW-ps laser pulses [1]. The radical new aspect appeared from comparing ion generation by laser pulses of more than 100 ps duration, with that of ps pulses. For long pulses, all the numerous observations in the past showed ion *energies in the dozens of MeV* for laser powers near TW linearly increasing on this power [2] as a result of relativistic self-focusing [3,4]. In contrast to this, Badziak et al [1] observed Cu^{+13} ions of *less than 0.5 MeV* only at these powers On top, there was no change of the number of these fastest ions when varying the laser power by a factor 30. It was essential that any prepulse has 10^{-8} times less power (contrast ratio) than the main pulse up to about 100 ps before its irradiation. A related observation by Zhang et al [5] was the low x-ray emission with sub-ps laser pulses at a similar contrast ratio, but when a prepulse 70 ps was used before the main pulse, high x-ray emission was detected. The obvious explanation was [6] that without the prepulse, no relativistic self-focusing was possible and a one dimensional plane wave interaction in the laser focus with the irradiated target could be assumed as calculated before extensively. The then possible skin-layer interaction [6,7] could immediately explain the constant ion number coming from the fixed volume of the skin-layer range. Confidence to this model was based on the fact that the numbers of maximum ion energies, x-ray emission, and quiver motion agreed with the measurements if a nonlinear force dielelectric swelling of reasonable number of about three was consistent.

In order to base this rather vaguely established skin layer model on more detailed numerical results, we present here a study how the blocks are generated, after experiments have confirmed the special properties of the ps interaction with high contrast ratio [8]. The ion emission against the laser light for TW-ps interaction showed only one group of plasma moving against the laser light where this ion group had a very low divergence in contrast to the long pulse interaction and where a number of fast ion groups was observed with the usual wide angle spread [9]. Another experimental result is the observation of the second fast ion group moving parallel to the ps laser light (compressing block) into the target. Very thin targets permitted the identification of this second group of fast ions of low angular divergence [8]. These experimental conditions permit then for the ps interaction, that one-dimensional plane wave computations can describe the processes in contrast to the self-focusing beam generating situation for the ns pulses, where examples are fully detailed two or three-dimensional computations [10]. The very detailed one fluid code is including collisions and their nonlinear deviation, separate electron and ion temperature and the stationary computation of the complete Maxwellian solution of the temporally changing laser field including reflection and following up the complicated hydrodynamic plasma motion due to gas dynamics and due to the nonlinear (ponderomotive) force density

$$f_{NL} = (\mathbf{n}^2 - 1)(\partial/\partial x)E_L^2/16\pi = -(\partial/\partial x)(E_L^2 + H_L^2)/8 \quad . \qquad (1)$$

Here **n** is the temporally and spatially changing complex refractive index for the laser light in the irradiated inhomogeneous plasma developing on the depth x and E_L and H_L are the amplitudes of the electric and magnetic field of the laser. The first formulation of (1) is known as ponderomotive force where the general case at oblique incidence required a number of clarifications with respect to the definitions [11] while the identical second expression in Eq. (1) refers to the more general formulation of the nonlinear force as the gradient of energy density. Fig. 1 shows how a neodymium glass laser pulse of 10^{18} W/cm^2 intensity irradiating a low reflectivity deuterium plasma produces a block of plasma after 1.5 ps moving with velocities up to 10^9 cm/s against the laser light and another block with similar velocities moving towards the plasma interior.

These earlier computations with nearly relativistic intensities showed the basic mechanism of block generation using a single-fluid plasma code. It was necessary to explore numerically the conditions of the experiment [8] with plasma thickness in the 10 μm range, though we are limited to laser intensities 50 below that of the experiment in order to have clear conditions of the double layer effects which can be followed up by using the genuine two-fluid code [18] specifically selected for the conditions of the experiment [8,9]. The code was updated with more numerical filtering in the advanced computers. Fig. 2 shows the resulting ion velocity v_i of a deuterium plasma irradiated by a rectangular neodymium glass laser pulse of 3×10^{15} W/cm^2 intensity of 4 ps duration where the initial electron and ion temperature is 30 eV and the initial density from the vacuum is a ramp of density increasing from $0.5n_{ec}$ linearly to $1.3n_{ec}$ at a depth x = 20 μm (n_{ec} is the critical density of 10^{21} cm^{-3}. A printout of the velocity profiles at different times is shown in Fig. 2.

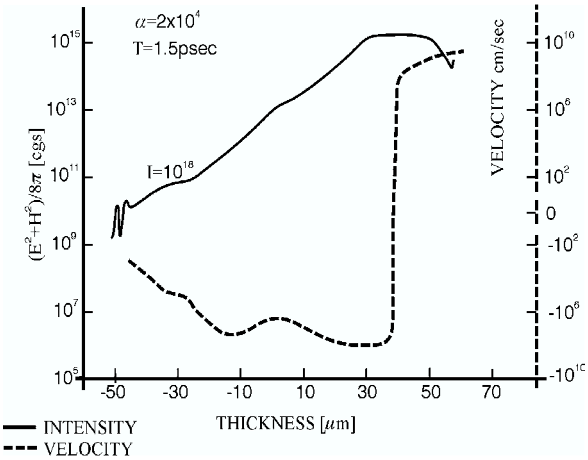

Fig. 1

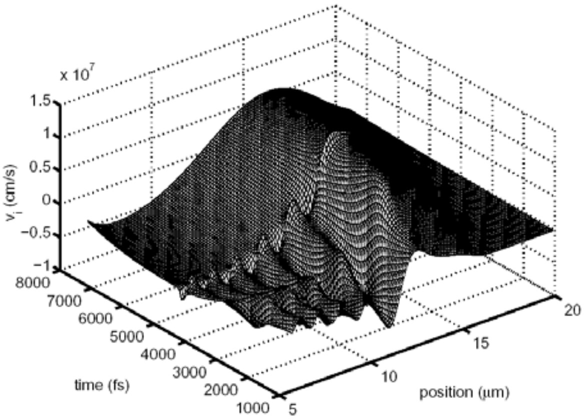

Fig. 2

For 2 and 4 ps we still see the oscillation in the plasma corona (below the critical density at about 12.5 μm) – well known from earlier computations [11] - but from 4 ps on we see the block of ablating plasmas (negative velocity in the corona since the laser comes from –x) and a block of plasma moving toward the plasma interior (positive velocities). The conditions were analysed analytically and indicated that the pulse duration was shorter than to reach the maximum velocity where the whole electron quiver energy of the electrons is converted into the energy of the compressing ions. For the shorter laser pulse τ_L the ion velocity can be expressed by

$$v_i = \text{const}\ \tau_L E_L^2 \qquad (2)$$

where the constant includes the dielectric swelling of the laser field and the thickness of the compressing block. The difference between 2 and 4 ps in Fig. 2 shows the doubling of the velocity of the compressing block for twice the laser interaction time τ_L. A detailed comparison the velocities expected from the simplified analytical evaluation shows agreement within 25%. The implications with light ion beam fusion are given now by comparison with earlier research from the application of the just described nonlinear force driven compressing plasma blocks moving into the plasma interior as discussed by several (Chu, Bobin, Kidder, Bodner, Ahlborn, Babykin, and Shvartsburg see Ref. [12]). A minimum value of incident energy flux for igniting a fusion detonation wave in uncompressed solid-state density DT was found to be 10^8 J/cm^2 for incident DT light ion beams. It was previously elaborated [12] that the inhibition of thermal conduction based on the double layer processes [13] and the collective effect of reduction of the stopping length [14,15] for the reaction products may reduce this limit to about

$$E_{ign} = 10^7\ \text{J/cm}^2 \qquad (3)$$

This estimate is based on the interpenetration of the beam of energetic ions and reaction products moving from the hot core plasma into the cold peripheral plasma to ignite the reaction wave. A further decrease of this threshold may be possible by the high temperature increase of the collision frequency due to the quantum modification going back to a remark of Bethe (1934) ([16] see also Chapter 2.6 of Ref. [4]). A rather pessimistic assumption is that given by Brueckner and Jorna for the ignition condition

[17]. Then the ignition by irradiation of the cold solid-state density DT plasma by fast DT ions on solid state DT requires a current density j

$$j \geq j_{BJ} = 10^{10}\ \text{A/cm}^2. \qquad (4)$$

As a pessimistic evaluation of these results for the ignition by the nonlinear force driven block generation we may use the density of the compressing DT block of the electron cut-off density n_{ec} and can choose an ion energy around 80 keV for the optimised DT reaction. In this case, the DT ion current density in the compressing block is $j = 4\times10^{10}$ A/cm^2. In the recent experiments [8], values of j in the range of 10^{10} A/cm^2 were measured. After this confirmation that the current densities of the blocks are high enough for the ignition of solid-state density DT plasma, the second condition is that the blocks have to be thick enough of the ignition. This is equivalent to fulfil the condition (3). Using the here described cases for neodymium glass laser pulses, the energy flux density is less than 10^6 J/cm^2 taking into account that in the best case, only a little less than 50% of the incident laser energy can go into the compressing plasma block, as confirmed numerically [4]. However, if the third harmonics of neodymium glass laser pulses of up to 1.8 ps duration are used, the condition (3) will be reached apart from the fact that then the current density j of the DT block again will be remarkably higher than (4) because of the nine times higher cut-off density. It is remarkable that lower laser intensities for just producing sub-relativistic blocks from the skin depth interaction produced higher fusion gains in the related experiments of Norreys et al [18] than when using relativistic higher intensities.

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