Ultrahigh Acceleration of Plasma Blocks from Direct Converting Laser Energy into Motion by Nonlinear Forces

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Abstract: In contrast to thermal pressure, 100,000 times higher acceleration of plasma blocks was predicted and measured by using nonlinear (ponderomotive) forces. This permits side-on ignition of uncompressed solid fusion fuel deuterium-tritium and hydrogen-boron11.

1. Introduction

Laser interaction with targets led to a fundamental discovery of nonlinearity. When laser pulses below megawatt (MW) power interacted, all was following classical thermal theory determined by hydrodynamics. Temperatures in the targets around 20,000 K led to the emission of ions of few eV energy and to classical plasma velocities. When Linlor [1] used the first Q-switched pulses of 10 MW, up to 10 keV ions (thousand times higher!) were measured. The ions had not thermally equilibrated energies but these increased linearly on the ion charge number fully indicating an electrodynamic acceleration in contrast to thermal effects. This led to the nonlinear (ponderomotive) forces determined by the optical dielectric plasma properties [2]. The nonlinearities were of basic nature, not only as a marginal correction to linear physics as know before. It was discovered that linear physics could be totally wrong and a little nonlinear change could lead to the correct results [3] where the tiny longitudinal (!) optical component of laser beams – without approximation derived by this way for the first time [3, Chapter 12.3] – was essential, leading to the "nonlinearity principle" [4]. This opened the way recently with the present petawatt (PW) picosecond (ps) laser pulses [5] - as Steve Haan from the largest NIF laser in the world in Livermore said in an interview with the Royal Society of Chemistry in London- that this leads to "the potential to be the best route to fusion energy" [6].

2. Initial prediction of ultrahigh accelerations as nonlinear process

The force density $\boldsymbol{f}$ in a plasma is determined by the gas-dynamical pressure $p = 3n_pkT/2$ where n_p is particle density, k is Boltzmann's constant and T the temperature and by the present electric and magnetic fields $\boldsymbol{E}$ and $\boldsymbol{H}$.

$$\boldsymbol{f} = \nabla p + \boldsymbol{f}_{NL} \tag{1}$$

For fields of a laser of frequency ω defining a complex optical constant $\boldsymbol{n}$ in the plasma, the nonlinear force is

$$\boldsymbol{f}_{NL} = \nabla\bullet[\boldsymbol{EE} + \boldsymbol{HH} - 0.5(\boldsymbol{E}^2 + \boldsymbol{H}^2)\boldsymbol{1} + (1+(\partial/\partial t)/\omega)(\boldsymbol{n}^2-1)\boldsymbol{EE}]/(4\pi) - (\partial/\partial t)\boldsymbol{E}\times\boldsymbol{H}/(4\pi c) \tag{2}$$

which is dominating if the quiver energy of the electrons in the laser field is larger than the energy of thermal motion [2]. For simplified one-dimensional geometry and perpendicular laser irradiation, the force (1) can be reduced to the time averaged value

$$\boldsymbol{f}_{NL} = -(\partial/\partial x)(\boldsymbol{E}^2+\boldsymbol{H}^2)/(8\pi) = -(\omega_p/\omega)^2(\partial/\partial x)(E_v^2/\boldsymbol{n})/(16\pi) \tag{3}$$

where E_v is the amplitude of the electric field in vacuum. This special case reminds of the ponderomotive force of electrostatics.

Computations for plane geometry interaction with inclusion of the nonlinear force interaction, of thermal laser absorption by collisions and equipartition processes in the dynamically developing optical plasma properties for interaction of neodymium glass laser irradiation of 10^{18} W/cm^2 intensity on deuterium having an initial Double-Rayleigh density profile [3, Figures 10.18a&b], arrived at a velocity distribution and an electromagnetic energy density as shown in Fig.1 after 2 ps interaction time [3] . The laser was irradiating from the right hand side and a plasma block was moving against the laser light and another one into the deeper target. The velocity at this time at the closest part to the laser was more than 10^9 cm/s. This corresponds to an average acceleration of more than 5×10^{20} cm/s^2.

3. Experimental confirmation of the ultrahigh acceleration by Sauerbrey [7]

The results of the computation were initially published in 1978 [3] but it took a long time [7] before an experimental confirmation of these ultrahigh accelerations was measured. The reason was not only the question how to produce the ps laser pulses of more than terawatt (TW) power, but there was the difficulty of relativistic self-focusing [8]. Each laser prepulse produced a plasma plume where any very intense laser beam was relativistically squeezed to less than wave length diameter producing very high intensities and emission of highly charged ions to energies far beyond MeV. Sauerbrey cut off the prepulses by a factor above 10^8 (contrast ratio), had then no focusing, and the then plane laser wave fronts were highly directed plasma blocks accelerated by 10^{20} cm/s^2 against the laser as immediately measured by Doppler Shift. This was in full agreement with the nonlinear force acceleration [9] as computed before, Fig. 1. Variations with respect to experimental accuracy were of minor nature for comparison in view of the significant fact that the ultrahigh accelerations were 100,000 times higher than the thermal pressure acceleration with the largest NIF laser.

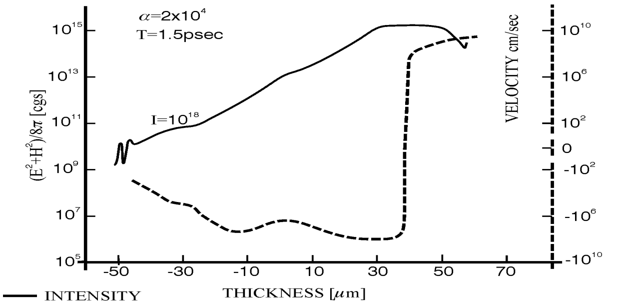

Fig. 1. Hydrodynamic computations in 1978 using 10^{18} W/cm^2 laser irradiation on deuterium close to the critical density resulted in a plasma block moving to the right against the laser light after 2 ps showing an acceleration of about 10^{20} cm/s^2 [3].

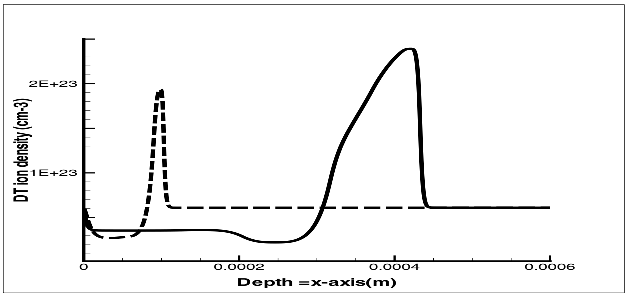

Fig. 2. Genuine two fluid hydrodynamic computations of the ion density in solid DT after irradiation of a laser Pulse of 10^{22} W/cm^2 of ps duration at the times 22 ps (dashed) and 225ps after the initiation.

4. Application to radical new laser fusion of solid density fuel

What was important with the ultrahigh acceleration, was that extremely high current densities in the highly directed space charge neutral plasma blocks arrived at 10^{11} Amps/cm^2 or more. This is again more than million times higher than accelerators could provide for ion beam fusion and permitted a comeback of the ignition of solid state – uncompressed or modestly compressed – fusion fuel by side-on ignition of a fusion flame. This was absolute impossible in 1972 [10] but this has changed now with the >PW-ps laser pulses [5]. It is potentially possible for energy production in power stations to achieve gains of 10,000 similar to the Nuckolls-Wood scheme using ps-laser produced very high density relativistic electron beams instead of the here treated nonlinear force driven plasma blocks.

For laser fusion of deuterium tritium (DT), extremely clean ps laser pulses with a contrast ratio above 10^8 may drive the controlled reactions in power stations with pulses of in the range of few dozens of PW power. These are close to technical realization. What was very surprising, is that the reaction of hydrogen and the boron isotope 11 (HB11) is less than ten times only more difficult than the DT fusion. This will generate less radioactivity in the entire reaction and in the waste than burning coal, per energy production [6][11]. Avoiding the need of extremely high fuel compression in the usual thermally ignited laser-fusion schemes, the side-on ignition is simplifying the process and it can be expected that power production can be at considerably much lower cost than present lowest cost sources [today's cost in Eurocents/kWh: nuclear fission 2, coal 5, wind 8, photovoltaic 38. (Source: TV-Deutsche Welle 23 March 2011)].

For the next exploration of the side-on ignition of laser fusion with nonlinear force driven plasma blocks, the initial computations [9][11] are now generalized to use the genuine two-fluid model [12] in order to study details of shock generation and very high electric field dynamics in the extremely inhomogeneous plasma in the fusion flame fronts. This is also for preparation of specific experiments with PW-ps laser of sufficient contrast to explore the revolutionary new scheme. Fig. 2 shows results of the ion density of the fusion flame when developing into solid density DT fuel after a ps laser pulse initiated the fusion flame. It is very interesting to see that the local ion density in the thin flame front moves with a velocity of 1.55×10^8 cm/s and the density in the flame front is four times higher than the DT. This is an automatic result of the genuine two-fluid computation [12] and agrees with the Rankine-Hugoniot theory of shock generation.

This summary could not include the support by other research as the discovery of the Particle In Cell (PIC) computations by Wilks et al. [13] reproducing and refining the hydrodynamic nonlinear force theory. Many crucial experiments [5][14] were supportive which all may be extended and focused to the new side-on fusion ignition.

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