Fusion flame in uncompressed fuel by nonlinear force driven Petawatt-picosecond laser pulses

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Abstract: An alternative fast ignition scheme with petawatt(PW)-picosecond(ps) laser pulses for producing a fusion flame was based on the fact that the nonlinear force can accelerate plasma blocks by 10^{20}cm/s^2 as predicted and measured. These plasma blocks are studied for side-on ignition by the updated Chu-Bobin fusion scheme and permits side-on ignition of uncompressed solid fusion fuel deuterium-tritium (DT) and hydrogen-boron11 (HB11).

1. Introduction

Laser pulses below megawatt (MW) power interacted classically resulting in target temperatures near 20,000 K with emission few eV ions. When Linlor [1] used Q-switched pulses of 10 MW, ions had thousand times higher energies, up to 10 keV and were not thermally equilibrated with energies linearly increasing on the ion charge in contrast to thermal effects. This led to the nonlinear (ponderomotive) forces modified by the optical dielectric plasma properties [2]. Evaluation of this nonlinear physics lead to new concepts [Chapter 12.3 of Ref.3, 1981] with consequences for laser driven fusion with petawatt (PW) picosecond (ps) laser pulses - 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” [4][5].

2. Ultrahigh acceleration of plasma by lasers as nonlinear process

The force density f in a plasma is determined by the gas-dynamical thermal pressure p and by the electric and magnetic fields $\boldsymbol{E}$ and $\boldsymbol{H}$ of the laser irradiation of frequency ω.

$$\boldsymbol{f} = -\nabla p + \boldsymbol{f}_{NL} \qquad (1)$$

The general nonlinear force $\boldsymbol{f}_{NL}$ with inclusion of the complex optical constant $\boldsymbol{n}$ (see Eqs. 8.87 and 8.88 of Ref. [6]) reduces for plane wave and one dimensional interaction to

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

where E_v is the amplitude of the electric field in vacuum. This formulation reminds of the ponderomotion in electrostatics.

Computations for neodymium glass laser irradiation of 10^{18} W/cm^2 intensity on deuterium having an initial Double-Rayleigh density profile (Figures 10.18a&b of Ref. [6]), arrived at a velocity distribution and an electromagnetic energy density as shown in Fig.1 after 1.5 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. Velocities at the closest part to the laser were more than 10^9 cm/s corresponding to an acceleration of more than 5×10^{20} cm/s^2.

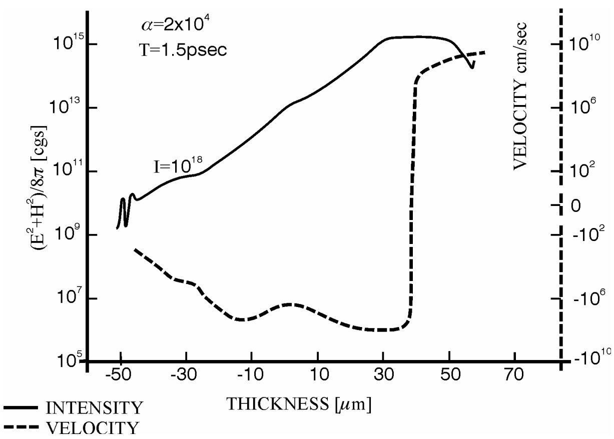

Fig. 1. Hydrodynamic computations in 1978 using 10^{18} W/cm^2 laser irradiation on deuterium close to the critical density resulted in a plasma block moving to the fright against the laser light.

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 generate 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's cut off the prepulses by a factor above 10^8 (contrast ratio), suppressed focusing, and the then plane laser wave fronts were highly directed plasma blocks accelerated by 2×10^{20} cm/s^2 against the laser as immediately measured by Doppler Shift.

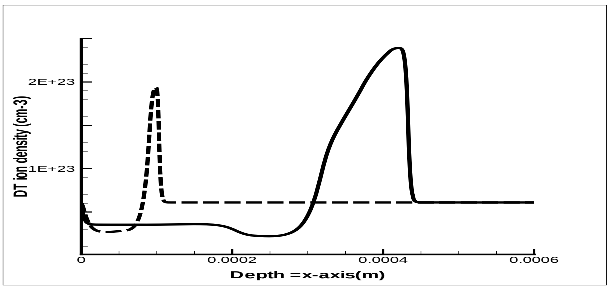

Fig. 2. Genuine two fluid hydrodynamic computations of the ion density in solid DT after irradiation of a laserPulse of 10^{20} W/cm^2 of ps duration at the times 22 ps (dashed) and 225ps after the initiation.

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

What was important with the fully clarified [9] ultrahigh acceleration, was that the directed space charge neutral plasma blocks arrived at 10^{11} Amps/cm^2 or more ion current densities. This relates to side-on ignition of a fusion flame. Following the initial computations of Chu in 1972 [10], this seemed to be completely impossible, but this has changed now with the >PW-ps laser pulses [9].

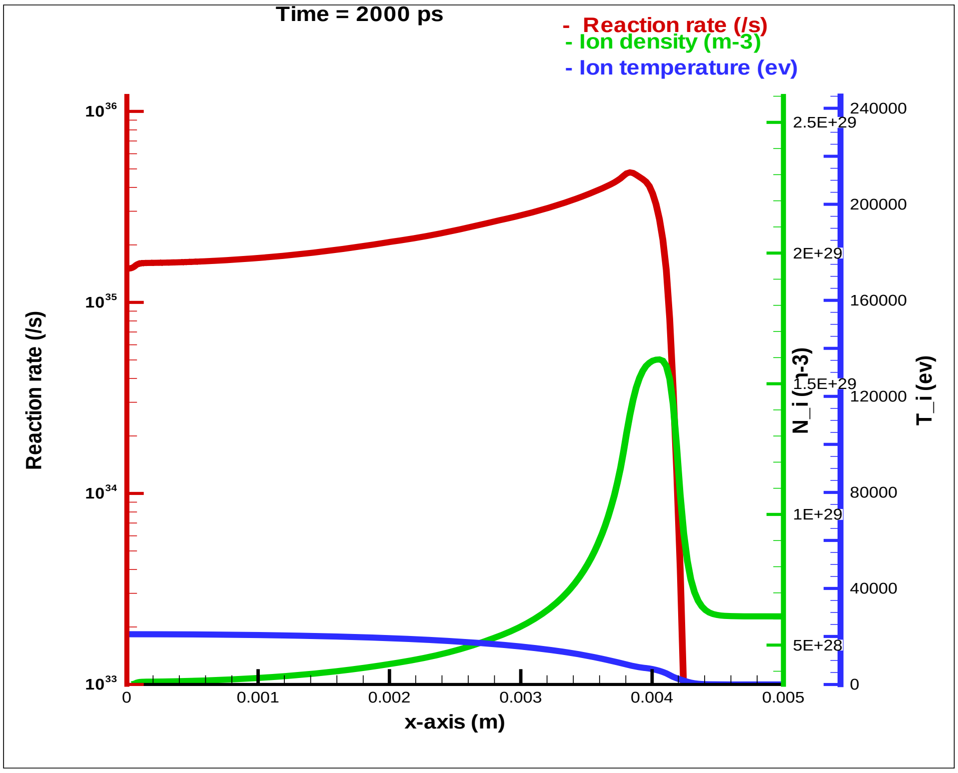

Fig. 3. Genuine two-fluid hydrodynamic computation for the time of 2000ps after a 2x10^8 J/cm^{2}laser pulse irradiated a 5 μm deep surface area of a solid density DT fuel. The reaction rate confirms that the fusion flame has penetrated 4.2 mm into the cold fuel, the flame has a plasma compression with in the limit of the Rankine-Hugoniot theory, a thickness of about 0.4 mm and a speed of 1300 km/s at this late time.

Upgraded single-fluid computations [5][9] showed that ignition of solid state density DT or HB11 may be possible. New computations with the genuine two-fluid hydrodynamics [11] showed many details about the development of the fusion flame. The ion density at different times showed the compression in the fusion flame by a factor four in agreement with the Rankine-Hugoniot theory and a speed to the flame of 1550 km/s (Fig.2). Another example for laser fusion of deuterium tritium (DT) is shown in Fig. 3 using KrF laser pulses as used initially by Sauerbrey [7]. Extremely clean ps laser pulses with a contrast ratio above 10^8 may drive the controlled reactions in power stations with pulses 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 [4][5].

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