SUPPRESION OF PULSATION BY LASER BEAM SMOOTHING AND ICF WITH VOLUME IGNITION

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ABSTRACT

A dominating mechanism responsible for the anomalies of the laser-plasma interaction at direct drive laser fusion is the 10 picosecond stochastic pulsation as recognised numerically and experimentally since 1974 and measured in many details by Maddever and Luther-Davies (Australian National University, Canberra) few years ago. These fundamental new results are now in the focus of interest in view of the present difficulties with the big laser-fusion facilities. A drastic reconsideration and economic solution may be possible based on our recent detailed numerical studies which indicate that the stochastic pulsation can be suppressed by an appropriate smoothing of the laser beam, permitting the operation with red light by saving expensive higher harmonic production avoiding damage by UV light, and providing much higher laser energy for fusion. By this way direct drive laser fusion will be favourable using the most robust volume ignition scheme with very high gain.

INTRODUCTION

The stochastic pulsation was recognised numerically by computations [1] in 1974 where the partial standing laser wave field in the plasma corona pushes the plasma to the nodes of the standing waves within few picoseconds. This self-generated density ripple is an ideal Laue-Bragg grating resulting in very high reflectivity at very low plasma densities prohibiting an energy input for the laser fusion. The subsequent hydrodynamic washing out of the ripple permits then after several picoseconds, again low reflectivity laser penetration of the corona with the mirror reflection at the critical density until a new rippling of the density cuts off the transfer of the laser energy to the plasma etc. This pulsation process was measured in all details by Maddever and Luther-Davies [2] where the Laue-Bragg phase reflection at the very low plasma density of the outermost periphery even was proved experimentally.

Using our genuine two-fluid hydrodynamic computations with all real time realistic mechanisms, the pulsation process was reproduced in many details [3]. Our code permitted the use of broadband laser radiation such that the expected result happened: the density rippling was avoided and a smooth and continuous transfer of laser energy with low reflectivity into the plasma could be shown. This confirmed that the long years observed laser beam smoothing is mainly a suppression of the stochastic pulsation as seen e.g. from the reduction by orders of magnitude of the detected second harmonics emission and parametric processes. The earlier assumed use of smoothing for suppression of ponderomotive self-focusing is less essential than the pulsation as immediately seen from pictures recorded by C.Labaune et al. [3,4]. This result encourages that laser fusion can be done in a very efficient way by direct drive if the necessary smoothing has been reached to suppress the stochastic pulsation. To the option of (isobaric or isochoric) spark ignition contrary to the volume ignition for laser fusion, the ideal isentropic property of the latter and the uniformity of pellet compression provide an enormous simplification and avoid symmetry problems. Volume ignition was therefore called “robust” by Lackner, Colgate et al (see Ref. in [2,5]). Following these results of smoothing for red light laser pulses and the success of volume compression [5] we present the results for direct drive volume ignition applied to the design of a MJ (red) light laser facility.

NONLINEAR FORCE INDUCED STOCHASTIC PULSATION

When studying laser-plasma interaction, the classical gasdynamic heating and expansion processes with ion energies of a few eV were achieved only for laser powers below about a megawatt. At 10MW and above, large numbers of 10 keV ions were emitted in the 10 keV range. Their energy distribution showed a series of peaks, one for each ionization number Z, with the energies of these peaks increasing linearly with Z. This dependence could never be brought about by gasdynamics and the large number of ions excluded simple electrostatic processes. The explanation was that electrodynamic forces dominate for the usual lasers with more than 10^{12}W/cm^{2} intensity. For the case of plasmas with a dielectric response, the “ponderomotive force” had to be modified to the general nonlinear force density [1].

$$f_{NL} = \frac{1}{c} j \times H + \frac{1}{4\pi} E\nabla.E + \left[1 + (1/\omega)(\partial/\partial t)\right] \frac{1}{4\pi} \nabla.(n^2 - 1)EE$$

Here the plasma has a complex refractive index n, which depends on the electron density n_e and temperature T through the collision frequency ν and the incident laser electromagnetic fields E and H have a frequency ω. The nontransient force was derived in 1969 [6] using momentum conservation while the complete transient force was derived 1985 [7] and the final generality was later proved Lorentz and gauge invariance [8].

A resurgence of the direct drive laser fusion process became possible when it was realised that the main problems of the interaction was the stochastic pulsation and not the parametric effect. Refined hydrodynamic computations in 1974 at the Institute of Laser Energetics at the University of Rochestor/NY included the nonlinear force and first demonstrated a devastating fact [10]. The laser light first penetrates into the plasma corona to the critical density region where a small fraction of the laser intensity is reflected, putting, as desired, most of the laser energy into the plasma for the fusion process. But the partially reflected light produces a standing wave field in the corona, which pushes the plasma into the nodes of the standing waves by means of the nonlinear force. This then produces, within picoseconds, a self-made ideal Laue-Bragg grating which causes a very high reflection of the incoming light within the very low-density plasma corona (see Fig. 10.10 of Ref. [11]) so that radiation no longer penetrates into the plasma. The plasma reacts in every way to prevent the incorporation of laser energy. After some picoseconds, the density ripple relaxes, the light again propagates to the critical density position and the whole process begins again as before. This pulsation of the reflectivity, of between a few percent and more than 95%, was observed by Lubin et al [12] but was not followed up seriously as most attention was focussed on parametric instabilities.

SUPPRESSION OF THE STOCHASTIC PICOSECOND PULSATION BY SMOOTHING FOR DIRECT DRIVE

Using a genuine two-fluid code [13], the generation of the density ripple, the low reflectivity, and the increase in the ion velocity during the first few picoseconds were reproduced. The acceleration stopped when there was almost no light in the corona (as seen in the plot of the electromagnetic energy density in Fig 1). During this time the thermal motion in the corona washed out the density ripple until the next time the light penetrated to the critical density region, the next plasma acceleration occurred and everything repeated from the beginning with the generation of the density ripple etc. The periodicity of this pulsation changed stochastically between 5 and 20 ps due to the complicated hydrodynamic processes, which accompany laser irradiation of intensity 10^{15}W/cm^2 at neodymium glass wavelengths [14] (see Fig 1).

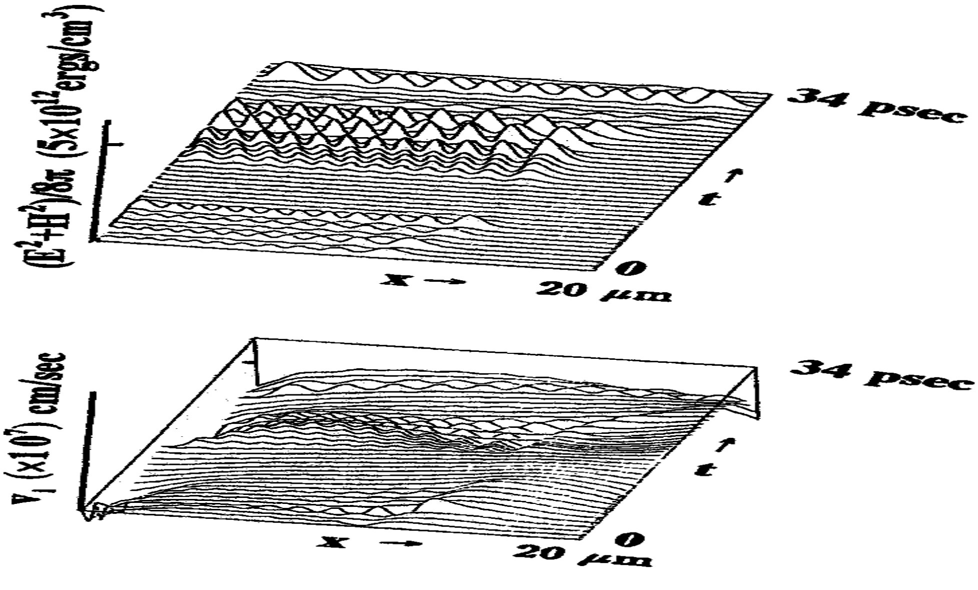

Fig 1: Neodymium glass laser irradiation with 10^{15}W/cm^2 intensity is incident on a plasma slab of 20μm thickness. The initial temperature is 30eV and the density grows linearly from 0.5 to 1.3 times critical density. The upper panel shows the time development of the electromagnetic energy density of the laser field $\varepsilon = \left(E^2 + H^2\right)/8\pi$ and the lower panel of the ion velocity in steps of one ps.

It shows the periodic penetration and stopping of laser energy occurring synchronously with the ion motion whose net value increases in blocks after each electromagnetic interaction with the corona. However when broad band laser irradiation of 0.5% band width was used in the computation, the standing wave rippling was not produced by the laser field and a perfect low reflection transfer of the laser radiation occurred leading to direct drive for laser fusion. This relates to the smoothing of laser beams by random phase plates (Kato et al [15] or temporal incoherence (Lehmberg et al [16]) which were suggested a few years earlier. The aim was to suppress filamentation by self-focusing but the measurements of Christine Laboune et al in 1992 [17] clearly showed that not only filamentation but also the pulsation of the whole corona front disappeared when the appropriate fine raster of a random phase plate was used. We conclude that the appropriate smoothing of laser beams, e.g. by the advanced methods using broadband irradiation [18] will permit direct drive laser fusion. The use of longer wavelengths is then possible where the three times higher laser energy in the red reduces the number of laser beams and the expensive generation of higher harmonics. While this may not affect the settled existing designs [19], the next generation may take this into account [20].

CONSEQUENCES FOR VOLUME IGNITION

For the next generation design of laser fusion facilities reaching the conditions of high-gain direct drive energy production, the use of long wavelength laser irradiation is now analysed using the process of volume ignition [21] like a diesel engine of the adiabatically compressed DT-fuel pellet [11]. This natural isentropic compression by laser ablation has reached the highest measured fusion gain [5]. This is in contrast to the shock generating attempts for the spark ignition as isobaric mode [22], which needs very exotic radial density, and temperature profiles for producing a fusion detonation front requiring an extreme arbitral symmetry. The surprisingly good agreement of the volume compression for measured highest gains [5] is shown in the lower left band part of Fig 2.

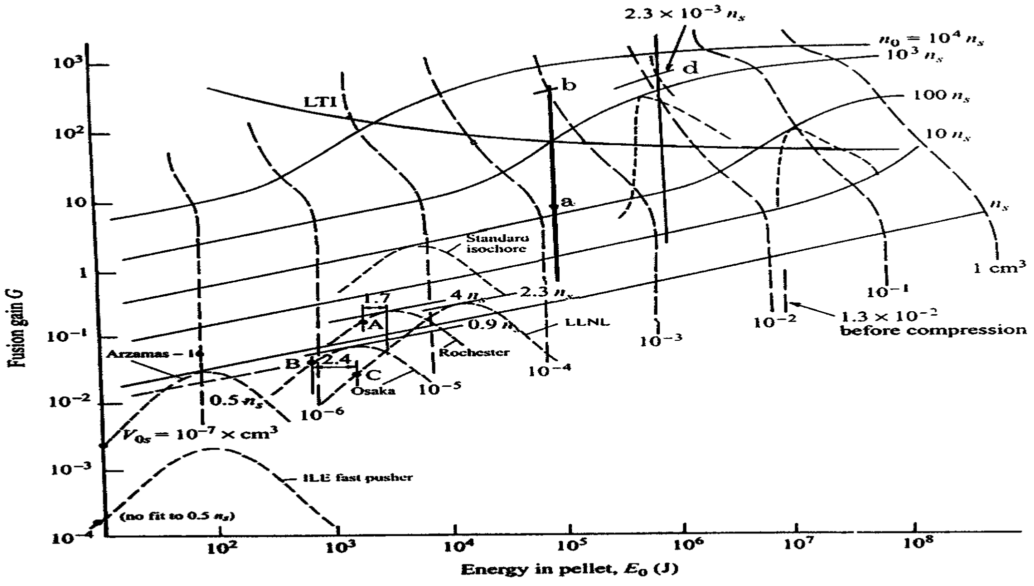

Fig 2: Fusion core gain G diagram[5] demonstrating volume ignition for appropriately smoothed red MJ laser pulses (a to b). A to C shows the perfect reproduction of highest gain direct drive laser fusion experiments with the (adiabatic, self-similarly) volume burn calculations (below core gain G=8) [5].

In all present experiment a core gain above 8 was not reached such that no strong self-heat by reaction products occurred leading to the ignitor. The range d in Fig 2 is from a comparison of the total (laser energy based) D-T fusion gains for laser pulses of 10MJ. Volume ignition reached a calculated 720MJ energy while spark ignition came to 1000MJ. For our application of pulsation free direct drive using a 1MJ LASER PULSE OF 1.053μm wavelength (red light), we follow up the vertical line going through a and b in Fig 2, assuming a low reflectivity 10% hydrodynamic efficiency. The (core) fusion gain of 8 is reached at a density of 112 times the solid state for the begin of ignition. Up to a density of 3000 times solid (b), the core gain is 300 or the total gain based on laser energy input is 30, which showed to be of interest for a fusion power station.

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