Fast Igniter Using Laser Driven Ultrahigh Intense Particle Beams

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Abstract: Irradiation of plasma by TW up to few PW laser pulses of ps duration is being studied since few years where numerous new phenomena were discovered. Within this broad stream of research very few experiments resulted *in most anomalous phenomena* which may be specifically distinguished and explained in the following since there may be an alternative application to laser driven fusion. Initially only the interaction of PW-ps laser pulses was considered for fast ignition (FI) [1] but modifications followed for using laser produced intense proton beams (proton fast ignition, PFI) [2] irradiating pre-compressed DT of about 1000 times the solid state. Application of 10 PW-ps laser pulses for producing very high intensity fife MeV electron beams, may lead to ignition of nearly uncompressed solid DT of larger volume controlled fusion reactions with gains above 10^4 [3]. In contrast to the usual techniques we discuss the application of the anomalous phenomena, where experimental and theoretical results show how laser driven very high intensity DT ion beams [4] may strongly improve the PFI. This is applicable also for *ion beam* ignition similar to the *electron beam ignition* scheme of Nuckolls et al. [3] using space-charge neutral plasma blocks [4] (plasma bunch or pistons [5]) with ultrahigh ion current densities.

1. Introduction

In contrast to the broad stream of interaction of TW to PW laser pulses of ps duration with plasmas, space charge neutral *ion beams of ultrahigh ion current densities* were produced by an unexpected new effect of skin-layer nonlinear-force acceleration of plasma blocks [6-10] for explaining some drastic anomalous observations. Since the acceleration of the ions is by the nonlinear force, the blocks (pistons) are highly directed and have a comparably low temperature. In the following we are mainly explaining this effect and discuss then the possible application for the proton fast igniter [2] where very much higher ion beam current densities are available with the plasma bocks and furthermore some aspects how the early concept of controlled fusion flame ignition [11] of only modestly compressed or solid DT fuel possibly may be achieved.

The new effect consists in the generation of plane geometry laser-plasma interaction [7, 12] in contrast to all the usual measurements where TW-ps laser pulses produced extreme relativistic effects in irradiated plasmas as 100 MeV electron beams, GeV highly charged ions, very intense x-ray or gamma-ray pulses with subsequent transmutations of nuclei by nuclear photo effect, pair production with very intense positron burst and further effects [13].

The following is mostly a recollection of the most abnormal experimental facts [6, 8, 9] - sporadically reported and covered within the broad stream of the usual facts - and their explanation based on much earlier theory of nonlinear (ponderomotive) forces and computations [7]. But this recollecting synopsis may have the value that unique new conclusions can be drawn on the proton fast ignition [2] and perhaps even about new aspects on very high gain laser fusion schemes with petawatt-picosecond laser pulses initiated by Nuckolls et al [3].

2. Sauerbrey's [6] experiment with 300fs-TW excimer laser pulses

Sauerbrey [6] studied the interaction of TW-ps laser pulses and measured the acceleration of plane plasma fronts moving against the laser light after being accelerated by very high values. This was indeed drastically different to all the measurements [13] known from the other numerous laboratories with the highly nonlinear relativistic effects. The main difference in the experiments of Sauerbrey [6] was that the laser pulses he used were exceptionally clean, i.e. with a suppression of prepulses (contrast ratio) of 10^8. Sauerbrey measured an acceleration A in a carbon plasma front by Doppler effect moving against the laser being produced by a 350 fs TW KrF laser pulse at 3.5×10^{17} W/cm^2 of

$$A_{exp} = 10^{20} \text{ cm/s}^2 \qquad (1)$$

This laser intensity I corresponds to an electric field

$$\mathbf{E}^2 = 2.9 \times 10^{15} \text{ erg/cm}^3 \qquad (2)$$

and a density $n_i m_i$ of the accelerated plasma layer of 5.4×10^{-3} g/cm^3 at the critical density

$$n_i = 1.6 \times 10^{21} \text{cm}^{-3} \qquad (3)$$

for C^{+6} ions. The nonlinear force for the simplified plane geometry [14] is

$$f_{NL} = - (\partial/\partial x) (\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) = n_i m_i A = - (1/16\pi)(\omega_p/\omega)^2 (d/dx) \mathbf{E}^2 \qquad (4)$$

Assuming for simplification dx = Δx = 10 μm and a swelling S = 2 (the experiments at similar conditions later by Badziak et al [7, 9] for ps pulses resulted in S = 3.5) we find the theoretical value

$$A_{NL} = 1.06 \times 10^{20} \text{ cm/s}^2 \qquad (5)$$

Applying this result to the accelerated plasma blocks of DT with a critical density at $n_e = 10^{21}$ cm^{-3} and ion velocity above 10^8 cm/s, shows that the plasma blocks have an ion current density above

$$j = 10^{10} \text{ Amp/cm}^2, \tag{6}$$

This type of plane, one-dimensional plasma block motion at the laser intensities used by Sauerbrey [6] for laser pulses in the range of ps *driven by the nonlinear (ponderomotive) force* were the earlier result of computations (FIG. 1).
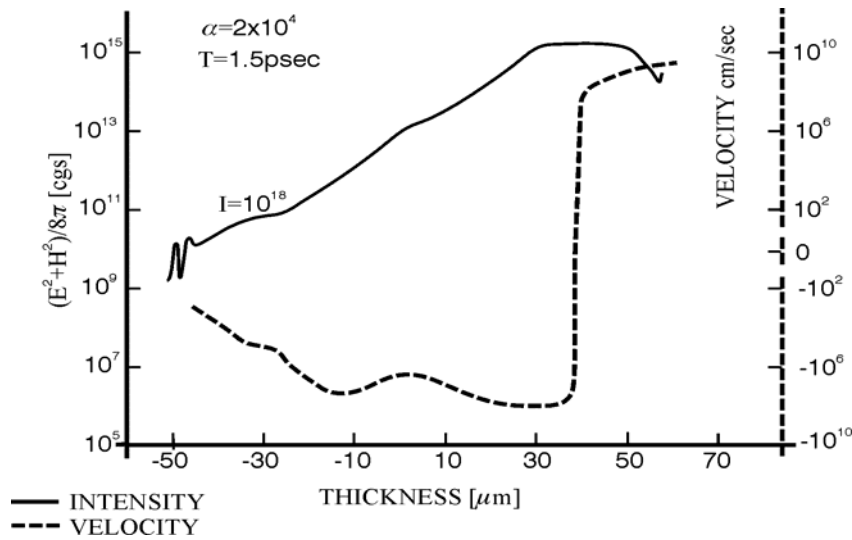

FIG. 1. Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100eV hot and 100μm thick bi-Rayleigh profile (FIG. 10.17 of Ref.[14]) with minimum internal reflection. The electromagnetic energy density ($E^2+H^2)/(8\pi$) is shown at the same time of 1.5ps after begin of the constant irradiation (Cang et al [15]).

3. Anomalous low x-ray emission (Zhang et al [8])

The next indication of a new effect was the anomaly in the measurement of x-ray emission by Zhang et al [8] at interaction of TW-ps laser pulses. Usually it was observed in all the experiments of high intensity laser-plasma interaction, that high intensity x-rays were emitted. The reason is that the laser beam undergoes relativistic self-focusing where the relativistic dielectric response of the plasma automatically results in a shrinking of the laser beam to a diameter of about one wave length [16] (see [17] and Chapters 12.2 and 12.6 of [14]). A necessary condition is that some prepulse of the laser produces a plasma

in front of the target of at least one to two times the diameter of the laser beam. This even happens if the laser beam is defocused to a very large diameter [18]. The very high laser intensity in the shrunk beam causes the emission of MeV to GeV highly charged ions with remarkable angular dependence [18] and high intensity hard x-rays.

The surprise was [8] that the interaction of the few TW-ps laser beam focused to more than 20 wave lengths diameter did not produced the high x-ray emission. The reason was that the laser beam has an enormous quality thanks to the techniques developed by Jie Zhang [18]. Similar to the Schäfer method used by Sauerbrey for the ps laser pulses [6], the usually applied Morou-CPA method used by Zhang et al [8] had a suppression of the prepulse by a contrast ratio of more than 10^8. In order to show this, Zhang et al [8] separated a laser pulse of less than few percent power from the main pulse to be fired it at varying times t_p to the target before the main pulse arrived. If t_p was 10 ps, nothing changed; the x-ray emission was staying on the low level. The same occurred for longer times up to 70 ps and more when suddenly the usual very high x-ray emission was measured.

It can simply be estimated [20] that during the prepulse at 70 ps before the main pulse, a plasma plume with a depth of about two times the interaction diameter on the target was produced. This is just sufficient at critical density that the relativistic shrinking of the laser occurs [14, 17]. What was discovered by Zhang et al [8] was that the strong suppression of *the prepulse prevented the relativistic self-focusing* similar to the case of Sauerbrey [6] without that this explicitly was realized.

4. Anomalous Low Energies of Emitted Ions (Badziak et al [9])

Measurements of the energy of the ions emitted against the laser beam from a target at irradiation of TW-ps laser pulses resulted in surprisingly low energies [9]. At the conditions of the focusing, copper ions of 22 MeV was the result when relativistic self-focusing occurred as in all usual experiments. Instead, the ion energy was half MeV only showing again the drastic anomaly of the effect. In order to compare with the usual observations, Badziak et al [9] measured the ion emission at very same experimental conditions with 0.5 ns laser pulses where the detailed results showed the usual behaviour.

Again it has to be underlined that Badziak et al [9] had very clean ps laser pulses where in retrospect it could confirmed that the contrast ratio could be estimated to be 10^8 at least until less than 50 ps before the main pulse hit the target.

The essential result to confirm the effect was the measurement [9], that the ps interaction resulted in a *constant number of fast ions* when varying the laser power over a factor 30. This was in contrast to all the usual observations of the fast ion emission from the laser irradiated targets.

5. The skin layer acceleration by the nonlinear (ponderomotive) force (Hora, Badziak et al [7])

Realizing the constant number of ions and the prepulse controlled relativistic self focusing, it became evident [7] that in all these cases of Zhang et al [8, 20] and Badziak et

al [9] with very strong suppression of the prepulse and avoiding relativistic self focusing – similar in retrospect also to Sauerbrey [6] – the interaction of the laser pulse was happening only in the skin layer of the irradiated plasma. Indeed some dielectric swelling processes could produce an effective corona with a skin layer of many vacuum wave length thickness as it was seen in the numerical output from several years before (FIG. 1) The skin layer volume was more or less constant why the number of ions for the nonlinear force acceleration (FIG. 1 and the evaluation in section 2 of this paper) was constant. No question was to understand that the fast ion energy at constant ion number [9] was linear on the varying laser power.

The confirmation of this skin layer acceleration (SLA) by the nonlinear (ponderomotive) force [7] was followed up experimentally and numerically in many details [9]. It was shown that the SLA mechanism resulted in measured highly directed plasma fast ion in clear contrast to the wide-angle ion emission at the usual relativistic self focusing. SLA generates a directed plasma block against the laser light and another block in the direction of the laser light into the target, as expected theoretically and numerically in all details (see FIG. 1); this was experimentally confirmed by irradiation of thin foils where the plasma block in the direction of the laser beam could be demonstrated. Comparison with SLA for gold ions of various charge Z and long pulse laser irradiation at simultaneous x-ray emission could be used to confirm analytically a dielectric swelling of the laser field in the plasma corona within the skin layer by a factor three. This was then consistent with very detailed numerical calculations with very general genuine two-fluid hydrodynamic codes.

6. Ultra-High Ion Currents for a Fusion Flame

It was underlined at the time of the discovery of the laser, that a use of radiation ignition for fusion reactions may be considered when applying laser radiation as envisaged 1960 by Nuckolls [21]. From his knowledge of radiation driven reactions is was interesting to be aware that the laser intensity of 10^{17} W/cm^2 is the intensity of Planck radiation of a temperature of 1 keV (11 Million degrees). Based on this fact it was a question whether the monochromatic long wave laser radiation can be compared with the Planck radiation of same intensity to ignite fusion fuel.

This question of directly igniting solid DT by a laser pulse was studied by Bobin [23] and indicated that is was practically impossible conditions when computations resulted in the fact that the fusion flame needs to have an energy flux density of

$$F > F^* = 10^8 \text{ J/cm}^2 \tag{7}$$

or an irradiation corresponding to an ion current density

$$j > j^* = 10^{10} \text{ Amp/cm}^2 \tag{8}$$

The condition for bean fusion (8) was by more than fife orders of magnitude out of possibilities for using particle beams as drivers. For achieving condition (7), Nuckolls

deduced the spark or central core ignition where the laser radiation (or after conversion into x-rays as "indirect drive", summarized by Lindl [24] compressed the DT in such a very sophisticated way producing isobaric a very hot but low density central core whose fusion reaction ignited into a surrounding low temperature high density mantle a very high gain fusion detonation wave (see FIG. 4 [25]). The reaction in the core was shown to be an ideal volume ignition and the energy flux density for driving the fusion detonation wave was in the range of $F = 7x10^8$ J/cm^2 fulfilling condition (7).

The result (6) reached with the SLA of space charge neutral plasma blocks provides the necessary high ion current densities (8) for igniting a fusion flame. But there are still further problems discussed in the following section such that more extensive studies will have first to be performed before a use of this scheme for laser induced fusion energy can be considered. A rather much closer result from SLA is the application to a modification of the fast igniter scheme [1] for a spark ignition using 5 MeV intense ion beams for energy deposition into the pre-compressed centre of the DT fuel [2]. I has been shown that the SLA mechanism can provide 1000 times high ion current densities [12,26] than achieved under the previous conditions [2] such that there is a support for nearly certainty that this scheme [2] may work though it needs fuel pre-compression to more than 1000 times solid.

7. Comparison with Modified Fast Igniter Schemes

The result (6) that the plasma block (piston) represents a fully directed space charge neutral DT beam of more than 10^{10} Amps/cm^2 with preferably 80 keV ion energy, provides a necessary condition for *ignition of a fusion flame in uncompressed solid DT* (Bobin [23]). For the condition (8) of the energy flux density of the block, it was estimated that the conditions even for the pessimistic values of condition (7) should be reached (FIG. 6 of [4]). The question is whether sufficient thermonuclear energy is produced to ignite the DT and whether the nonlinear force driven plasma block (or called piston plasma bunch [5]) has not a too low mass per area that it will blow apart before enough thermonuclear energy is generated. The question is how to correlate the results with that of ignition of 12 times solid state density DT by the relativistic electron beam from a 10 PW-ps laser pulse [3], and how even a lower DT density may be possible.

Taking the case of Storm et al for spark ignition (see FIG. 4 of [25]), the evaluation arrived at the volume ignition of the plasma core of a temperature of 12 keV of 200 times solid state density containing 430 kJ to ignite a fusion flame into the surrounding high density mantle at a value of 7 g/cm^2 for producing a gain of 100 of fusion energy per input total laser energy. A mechanism for a sufficiently thick plasma block to avoid that the piston [5] is blowing apart, may be reached by using spherical irradiation geometry (FIG. 6 of [12]). This was first aimed to improve the proton fast ignition scheme of Roth et al [2] by a factor 1000 by using the plasma block generation, but the same geometry can be used also for generation of a thicker piston. When the first compressing DT layer is produced e.g. of 10 vacuum wave length thickness (red arrows in FIG. 6 of [12]) and when this moves spherically to the centre, its low thermal energy will cause an expansion

of the thickness of the layer. In order to keep or even to increase the density in the directed high ion energy of ballistic block motion, the concentric moving block layer increases the density while the block is getting thicker. The mechanisms involved are indeed complex – even when avoiding the usual relativistic effects [13] – as it was seen from large focus area irradiation jet generation [27] or directed sidewise electron jets [28] with interaction with the laser beam produced magnetic fields in the plasma [29].

For generating the fusion flame [23] it has to be evaluated, how the interpenetration process of the energetic directed block ions into the cold DT fuel is improving the conditions on which the energy flux density, Eq. (7) is based. At least a reduction by a factor 20 was shown [30] due to the interpenetration process. What more has to be included into these studies is the increase of the electron-ion collision (anomalous resistivity as clarified by a quantum modification, see [14] Sect. 2.6), the inhibition of thermal conduction as explained by a double layer mechanisms [14], the increase of the stopping length of the nuclear reaction products by collective effects (see [14] p. 337), and a stochastic analysis of the interpenetration. Indeed there is no question that a block (piston) ignition of uncompressed DT without any pre-compression would enormously simplify a fusion reactor for very low cost energy production.

8. Conclusions

In conclusion, interaction of TW-ps laser with plasma results in a skin layer mechanism for nonlinear (ponderomotive) force, driven two dimensional plasma blocks (pistons). This mechanism relies on a high contrast ratio for suppression of relativistic self-focusing. Space charge neutral plasma blocks are obtained with ion current densities larger than 10^{10} Amp/cm^2. Using ions in the MeV range results in 1000 times higher proton or DT current densities than the proposed proton fast igniter requires [2]. This should result in better conditions of this fast ignitor scheme. The ballistic focusing of the generated plasma blocks and then short time thermal expansion increases their thickness but keeps the high ion current densities. As shown here, this approach then provides conditions that are very favorable for efficient fast ignition of a fusion target. If successful, this approach to fast ignition could significantly simplify operation of an IFE plant, allowing very attractive energy production costs.

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