Experimental problems with very high contrast and laser beam smoothing for impact fusion and block ignition

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Abstract. Ultrahigh acceleration of plasma blocks by laser pulses of higher than about terawatt (TW) power and of about picosecond (ps) duration reached values above 10^{20}cm/s^2 as measured from Doppler effect. These accelerations are more than 10,000 times higher than ever measured from thermal mechanisms by gas-dynamic pressure and agree with earlier computations using the nonlinear (ponderomotive) force. The separation of thermal and electrodynamic acceleration needs a clarification of several complex experimental problems.

1. Introduction

Sauerbrey [1] discovered from measurements with the Doppler effect, that plane plasma blocks are accelerated by 10^{20} cm/s^2 using TW-ps laser pulses. This succeeded only after it was possible to suppress laser pre-pulses by a contrast of 10^8. A confirmation of this condition was shown by Zhang et al. [2] where relativistic self-focusing of the laser beam in the plasma was suppressed. This exclusion of relativistic self-focusing was necessary in order to provide the presumptions of earlier (1978) computations with plane geometry plasma irradiation where exactly these high accelerations were derived for 10^{18}W/cm^2 laser pulses of 1.5 ps duration. In these calculations the predominance of acceleration by the nonlinear (ponderomotive) force, see Fig. 1, was shown in contrast to acceleration by thermal processes.

Another confirmation was given by the experiments by Badziak et al. [4] where the emission of the fast ions from the target was highly directed perpendicular to the surface and the intensity independence of the ion number could be explained [5] from the dielectric highly increased skin depth region [6]. Subsequent experiments and computations confirmed this process [3]. These experimental facts of ultrahigh accelerations and the agreement with nonlinear interaction theory were well evident and proved. On the other hand, the clarification between these different complex processes is still under discussion where the selection of transparent experimental conditions is still on the way. This is the reason why a careful examination of the involved process is necessary for the ongoing studies. This led to side-on ignition of uncompressed fuel following an improved Chu-model [7][8], even with uncompressed p-^{11}B (HB11) fuel producing nuclear energy with less radioactivity then burning coal [9]

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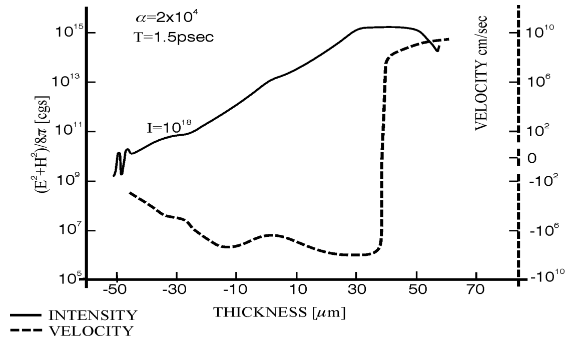

Fig. 1. Interaction of a 10^{18}W/cm^{2}neodymiumglass laser intensity with a deuterium block of initial Rayleigh density profile after 1.5ps interaction showing more than 15 wave length deep plasma layer moving in the outermost part against the laser, incident from the right hand side, with velocities of more than 10^9cm/s see Fig. 10.18a&b of Ref. [6].

2. A fundamental consideration

The petawatt-picosecond laser interaction with targets opened a basic new field of physics what is mostly related to clarify the mix-up between temporally delayed thermal gasdynamics against instantly acting direct electrodynamic mechanisms. The fundamental problems were formulated by Edward Teller in 1952 by considering the time delayed mechanisms for controlled nuclear fusion reactions for energy production in view of the then formulated new theory of complex systems (see [10]) in connection also with their stabilization by Lord May (see his recent applications [11]). Teller praises to aim the use of very fast processes to overcome the well known instabilities etc.. It may well be that the nanosecond laser-fusion [12] is of fundamental difference to the picoseconds case [8][9].

Gaillard et al [13] summarized the confusing difficulties with the high-power ps pulses by most detailed measurements [14] following the result of Sauerbrey [1]. Any consideration in thermal categories failed when taking the extremely low measurement of hot electron energies. These low energies can be explained immediately by the collisions of the quivering electrons during the electrodynamic interaction processes [5][8]. The same consideration applies also to the measurement of the 62MeV proton emission independently of the irradiated substance [13] with an intensity $I=6x10^{20}$ W/cm^2 of neodymium glass laser pulses. Taking the kinetic energy part of the electron quiver energy of the vacuum laser field of $I/(2cn_{ec})$ with the critical electron density n_{ec}, the value is 62MeV. This reminds that the nonlinear force without swelling in the peripheric outermost interaction range has dragged out the proton cloud and then the process of converting the kinetic energy part of the quiver energy into translative proton motion appears in the same way as known from the radial emission of electrons from a laser beam [15].

In the outermost range, the conditions are rather simplified without swelling [5]. For the following heavier ion groups separated by charge number Z, the swelling is dynamically changing temporally and spatially, such that any analysis will be very complicated even if thermalization effects are of minor influence as seen from the general numerical analysis [3][16]. These hydrodynamic studies are indeed to be supported by particle in cell PIC computations where agreement with hydrodynamics at the interesting laser intensities was proved [8]. Nevertheless, the dielectric properties of the plasma given by the dynamically varying optical constants in space and time is a problem in the PIC studies.

The dominating electrodynamic processes in contrast to the thermokinetics at nanosecond laser pulses are well described as “direct laser-light-pressure acceleration” [13] while “nonlinear (ponderomotive) forces” does not specifically charcterize the essential properties. For the latter expression it is to remind, that the forces for instantly acting by the laser energy on the space charge neutral electron cloud is determined by the description of forces which are given always by square expressions [17] of fields including electric currents which are linearly related to fields by Ohm's law. The difference of the nonlinear to the linear definition of forces is given from the linear relation by Coulomb's law.

3. Repetition of the Doppler experiments

Before considering the mentioned basically new kind of categories happening in the picoseconds range of interaction in contrast to thermal processes for longer puls interaction, we mention the initial experimental problem of the suppression of relativistic self-focusing. A repetition of the ultrahigh acceleration of plasma blocks [1] measured by Sauerbrey was successful by using a reconstruction of an independently developed KrF laser system [20][21] by measuring the Doppler effect [22][23]. With a laser intensity of 2.6×10^{15} W/cm^2 for 700 fs laser pulses with sufficiently high contrast ratio the generated plane geometry plasma front arrived at a velocity of $1{,}25\times10^7$ cm/s of the plasma block at irradiation of aluminium. The measured acceleration is

$$a = 1.6x10^{19} cm/s^2. \quad (1)$$

The laser intensity was lower than in the initial experiment of Sauerbrey [1] but again, the acceleration was at least about 2,000 times higher than any acceleration of plasma blocks driven by temperatures in the plasma dynamics using ns laser pulses [24].

Apart from this clear fact of the acceleration as in Eq. (1) there were well known difficulties how to provide the necessary experimental conditions. One problem may be that the KrF gas lasers may not have to eliminate hot spots in the laser beams as solid state lasers with the nonlinear dielectric responses in the laser material. This was discussed in connection with related laser-target interaction processes [18][19].

The significant example how solid state lasers can be operated with extremely high contrast ratio and avoiding relativistic self-focusing is the experiment by Zhang et al. [2]. Before the experiments by Sauerbrey [1] and Zhang et al. [2], all led to relativistic self-focusing at the high laser intensities with subsequent MeV to GeV emission of highly charged ions and very intense hard x-ray emission. This could be suppressed only by the extremely high contrast ratio. Zhang et al [2] systematically used prepulses irradiating the target by up to 100 ps before the main pulse arrived. The generated plasma plume led to self-focusing only above 70 ps as measured by the subsequent change from very low x-ray emission to the usual high levels.

It may be that the detection of very low x-ray emission is a sufficient prove for avoiding relativistic self-focusing while the checking by the Doppler effect involves many more qualities of the experiment which may not be needed for the generation of the nonlinear force driven plasma blocks, at least for the next systematic experimental campaigns to study the specific properties of the high power interaction of ps laser pulses. These aspects were at least derived from unpublished experimental results [19].

4. Conclusions for preparation of the next experiments

The here elaborated considerations summarized some aspects for design of the experiments with the aim for generation of ultrahigh acceleration of plasma blocks not only for the side-on ignition of solid density or modestly compressed fusion fuel [3][8][9] but also for related schemes of shock ignition or impact fusion [24][25]. The basic difference between the thermo-kinetic driven acceleration processes with nanosecond laser pulses in contrast to the nonlinear force dominated instant electrodynamic driving with picoseconds laser pulses was underlined. This needs a very clear distinguishing by the diagnostic techniques and for theoretical and numerical analysis of the processes.

The preparation of the laser pulses with extremely high contrast ratio is essential. The experience of Zhang et al. [2] with the elimination of relativistic self-focusing by detecting the low x-ray emission is at least a first necessary condition for checking each experiment as a kind of routine for all cases to exclude a confusion with the usual effects known from measurement with too low contrast ratio. In view of confirming sufficiently plane laser wave fronts for the interaction with suppression of hot spots for confirming the conditions which were necessary for the Doppler measurements, it is rather interesting to see that this was well possible when using KrF laser pulses of shorter than ps duration [1][22][23]. The use of solid state lasers was proved to be possible too as seen from the experiments of Zhang et al [2]. A further proof of the conditions of plane wave front acceleration can be confirmed by measuring the highly directed motion of the fast ions as in the initial cases using solid state lasers [4] and confirmed in details later [26][27].

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