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SHORT COMMUNICATION

Fundamental difference between picosecond and nanosecond laser interaction with plasmas: Ultrahigh plasma block acceleration links with electron collective ion acceleration of ultra-thin foils

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Abstract

Arguments are discussed on how ion energy measurements from ultra-thin diamond irradiation with 45 fs laser pulses of 26 terawatt power may be related to the ultra-high acceleration of plasma blocks where the significance of the highly efficient direct conversion of laser radiation into mechanical motion of ions or plasma blocks is dominated by nonlinear (ponderomotive) forces in fundamental contrast to thermo-kinetic dominated interaction with ns laser pulses.

Keywords: Laser-plasma interaction; Nonlinear (ponderomotive) forces; Non-thermal process; Picosecond pulses; Ultra-high acceleration; Ultra-thin targets

Interaction of picosecond laser pulses of terawatt and higher power with targets was studied extensively with thin foil targets of which the results with several nm thick diamond-like carbon (DLC) was of interest (Steinke *et al.*, 2010). These ultra-thin targets with plasmas of much larger Debye length λ_D than the target thickness D could be considered to be essentially different from thicker targets where $D >> \lambda_D$. The following research note may show how analytical models may arrive at comparable results for explaining the measurements. The reason is obvious that the picoseconds pulses follow a different category of interaction than the usual descriptions by thermal processes.

A fundamental difference appeared in a drastic way between the interaction of high power laser pulses if their pulse duration is in the range of picoseconds and shorter versus the range of nanoseconds. The advent of the picosecond laser pulses with more than terawatt and petawatt power (Perry *et al.*, 1994; Mourou *et al.*, 2002) — motivated by the new concept of fast ignition for laser fusion (Campbell, 2005; Tabak *et al.*, 1994) — led to the essential confirmation that the force density in plasmas is determined by two components. The thermo-kinetic part is given by the pressure p from thermal motion of the particles and the other part is given by the nonlinear (ponderomotive) force $\boldsymbol{f}_{NL}$ for the electro-dynamic interaction of the laser

$$f = -\nabla p + f_{NL}. \tag{1}$$

The drastic difference can be seen from the ultra-high acceleration of plasma blocks measured first with modest KrF ps laser pulses by Sauerbrey (1996) and clearly repeated (Földes, 2000) in the range of 10^{20} cm/s^2 as predicted numerically (Hora, 1981, see p. 178; Hora *et al.*, 2007: Fig. 1 of this reference) while the present largest lasers with ns pulses arrive at plasma accelerations about more than10000 times lower (Karasik *et al.*, 2010). It is important to mention that the mixing of thermal and nonlinear processes on the way to Sauerbrey's result was well noticed (Kalashnikov *et al.*, 1994) but a special evaluation of the Doppler effect was needed for the experiment of Sauerbrey (1996) where exclusion of relativistic self focusing was essential (Zhang *et al.*, 1998; Hora *et al.*, 2007).

For understanding the measurements with the ultra-thin diamond it was found "that all the existing analytical models fail to even qualitatively predict the two main features seen experimentally" (Steinke *et al.*, 2010) and the Mako-Tajima model for a collective driven electron dynamics for

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efficient ion acceleration (Mako *et al.*, 1984) arrived at a reasonable explanation. The Mako-Tajima model was developed for studying intense electron beam interaction with thin plasma layers with the result for the evaluation by Steinke *et al.* (2010) that there is a "collective" generation of electrons moving into one direction without having thermal properties determining the acceleration of the comparably very large number of ions.

This is in full analogy to the nonlinear (ponderomotive) force for explaining (Hora *et al.*, 2011) the measured ultra-high acceleration of plasma blocks (Sauerbrey, 1996; Földes, 2000), which application to the modification of fast ignition for side-on generation of a fusion flame in solid density fuel is of interest (Hora *et al.*, 2010, 2011*a*, 2011*b*; Lalousis *et al.*, 2012). In the numerical prediction of the plasma block acceleration to $10^{20}\,\mathrm{cm/s^2}$ (Hora, 1981), the electron cloud (like a collective) is instantly and without thermal losses receiving the acceleration in the laser field by direct conversion of nearly 100% of laser energy into mechanical motion where — due to the small Debye length — the acceleration of the plasma block is defined by the mass of the attached ion cloud.

Although there is no simple analogy of the motion of the plasma block where the Debye length had to be much smaller than the plasma block thickness, it is very remarkable that the thin layers showed acceleration in the direction of the laser propagation in strong contrast to symmetric acceleration (Andreev *et al.*, 2008). The directed co-moving electrons and ions significantly seem to confirm the electro-dynamic interaction in contrast to thermal processes. On the other hand, it should be warned that even small contributions of collisional thermal processes can cause as this all had been covered in the analysis of Mora (2003) and as it is included also well in the genuine two-fluid code (Laousis *et al.*, 1983; Hora *et al.*, 1984). This may change even the now resulting electro-dynamic domination at conditions close to poles of the involved functions. An example is the resonance absorption (see Hora, 1981, chapter 11.2) where the result without collision with a negative pole changed into a very high positive value due to a very small dissipation process by collisions or Landau damping. The only difference may be that the electro-dynamic process has to be considered as a macroscopic dissipation process of converting optical energy into macroscopic motion of plasma or ion groups.

There seems to be no question that the interaction time of 45 fs is too short for thermalizing the quivering electron motion and the collective laser-driven electron dynamics for the efficient ion acceleration. This has similarities to the interaction of a relativistic electron beam interaction with a plasma layer (Mako *et al.*, 1984). The thin foil experiment (Steinke *et al.*, 2010) with a much larger Debye length than the depth of the DLC target may be much different to the ultra-high acceleration of the plasma blocks (Sauerbrey, 1996) where the Debye length is much shorter than the thickness of the generated plasma block. Nevertheless, the conclusion of the non-thermal plasma collective processes for driving the ions of the very thin foil (Steinke *et al.*, 2010) has an analogy to the very clear result that the plasma blocks are driven by nonlinear (ponderomotive) forces through the laser energy conversion into the directed motion of the electron cloud where the inertia is determined by the attracted ion could of the plasma (Hora *et al.*, 2007; Hora 2009). It is interesting that there is a convergence (Mako *et al.*, 1984) of the electron collective model of Mako and Tajima with the hydrodynamic result of the predominance of the nonlinear force interaction (Hora, 1969) showing the ultrahigh acceleration of $10^{20}\,\mathrm{cm/s^2}$ (Hora, 1981, Figs. 10.19a and 10.19b) as measured by Doppler shift (Sauerbrey, 1996; Földes *et al.*, 2000).

The conditions with the Debye length are different to the ultra-thin DLC target, and in a more heuristic way, comparisons will be considered. There are two facts of interest in the experiments of Steinke *et al.* (2010). The first is that an initially thickness $D = 18$ nm DLC foil has a nearly zero transparency for the 45 fs laser pulses. This needs to be discussed in view that D is then 2% of the vacuum wave length. The second is that the generated intense and directed C^{6+}-ions have energy within the experimental errors to six times of the proton energy. This is first of the fact that there is a linear dependence of the ion energy on the charge number Z as result of the nonlinear force acceleration (Hora, 1981, Eq. (9.21)). The mass difference of the ions is not connected with the ion energy and may be seen if one would measure the ion energy of the fastest C^{1+}-ions which should be the same as that of the protons.

Whether the mentioned question of the Debye length is a limit, depends whether space-charge quasi-neutral conditions are needed as in one-fluid plasma hydrodynamics which is the basis of the equation of motion using the elimination of local electric fields in the plasma when adding and subtracting the separate hydrodynamic equations for electrons and for ions (Hora, 1981, chapter 8) following Schlüter's (1950) two-fluid model. The theorem that there are no internal electric fields in plasmas (Kulsrud, 1983) had to be given up in favor of the results of Alfven (1981) about the internal electric fields. This was seen also from the derivation of the nonlinear force from single electron quiver motion in the laser fields (Hora, 1991, Fig. 8.1) where the conversion of quiver energy into energy of translation is to be discussed. This was explaining the measurement of the lateral emission of electrons from a laser beam as a nonlinear force effect (Boreham *et al.*, 1979) as a quiver drift. For the axial acceleration, only the excess of the dielectrically increased quiver energy after subtraction of the vacuum value of the quiver energy acted for the motion against the laser light. These facts led to the development of the "genuine" two-fluid computations where the electric fields in the plasma were included (Lalousis *et al.*, 1983; Hora *et al.*, 1984).

For the conditions of the experiment (Steinke *et al.*, 2010) one needs to include the dielectric increase of the amplitude of the electric field $\boldsymbol{E}$ for the quivering by the dielectric constant n over the electric field of the laser in vacuum $\boldsymbol{E}_v$

expressed by

$$E = E_v/n = E_v S^{1/2}, \tag{2}$$

where S is the swelling factor. The general Lorentz and gauge invariant nonlinear force in Eq. (1) (Hora, 1991, Eq. 8.88) is reduced to simplified one dimensional plane wave conditions to

$$\begin{aligned} f_{NL} &= -(\partial/\partial x)(E^2 + H^2)/(8\pi) \\ &= -(\omega_p \omega)^2 (\partial/\partial x)(\mathrm{E}_v^2/n)/(16\pi), \end{aligned} \tag{3}$$

where $\boldsymbol{H}$ is the magnetic field of the laser of frequency ω. Using the quiver energy of the electrons in the laser field (Hora, 1981, Eq. (6.76), neglecting a correction factor A close to unity)

$$\varepsilon_{osc} = mc^2[(1 + 3I/I_r)^{1/2} - 1], \tag{4}$$

where I is the laser intensity, m is the rest mass of the electron and the relativistic threshold intensity. The relativistic threshold intensity I_{r} is that resulting in quiver energy of mc^2

$$I_r = (3c/8\pi)(m\omega c/e)^2. \tag{5}$$

The abbreviation a_L is commonly used for the expression in the Lorentz-factor in Eq. (4)

$$a_L^2 = 3I/I_r, \tag{6}$$

where e is the electron charge in *cgs*. In order to fit the reported measurement of 13 MeV proton energy, the dielectric increase of the laser field amplitude within the generated plasma from the ultra-thin DLC would need a dielectric increase by a factor 2.69, which value is rather reasonable compared with similar cases.

One may speculate how a dielectric response in the plasma is produced from an 18 nm thick diamond layer by the 45 fs laser pulse. There is no information about the pre-pulse during the last ps before the 45 ps pulse is interacting and whether inhomogeneous plasma is produced at the diamond surface. The nearly instant complete ionization of the carbon is confirmed from the measurement of C^{6+}-ions. This will produce a highly overcritical electron density. Why would then be no tunneling of laser energy through a layer with a thickness of 2% of the vacuum wave length? Very probably there is an anomalous nonlinear absorption where the laser energy is converted mostly into ion energy. The analysis, however, needs many more details of the experimental results. This will be of special interest for the interaction processes in the attosecond range (Krausz *et al.*, 2009).

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