Nonlinear Force Driven Skin Layer Acceleration of Plasma Blocks

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Abstract. Since the interaction of ps laser pulses of TW power with plasmas was measured, an anomalous process was discovered which was significantly different from the usually observed numerous relativistic phenomena. This could be explained by earlier extensive numerical studies. Applications for laser fusion are reported for the generation of thick plasma blocks for ignition of fusion flames. For irradiation of spherical DT shells, the ablation efficiency may be ten times higher for the nonlinear force driven plasma blocks for volume ignition.

1. Nonlinear ( ponderomotive) forces at laser-plasma interaction

Laser interaction with plasma at powers above MW changed drastically. Below MW, the force density \( f = f_{th} + f_{NL} \) was described by the thermokinetic value \( f_{th} = -\nabla p \) with the pressure \( p \), and above MW being dominated by the nonlinear force density

\[
f_{NL} = \nabla \cdot (EE + HH - 0.5(E^2 + H^2) \mathbf{I} + (1 + (\partial / \partial t) / \omega)(n^2 - 1)EE) / 4\pi - (\partial / \partial t)E \times H / (4\pi c) \]  

where \( E \) and \( H \) are electric and magnetic fields of the laser of frequency \( \omega \), modified by the complex dielectric constant \( n \) of the plasma and \( \mathbf{I} \) is the unity tensor [1,2]. For plane plasmas irradiated perpendicularly (x-coordinate) by lasers, Eq. (1) reduces to,

\[
f_{NL} = (n^2 - 1)(\partial / \partial x)E^2 / 8\pi = - (\partial / \partial x) (E^2 + H^2) / 8\pi \]  

This is formally identical with the electrostatic ponderomotion (electrostriction) or generally expressed as negative gradient of the electromagnetic field energy density. The MW laser power is just the threshold for self-focusing [2:Sect. 12.1] explaining the very high energy of ions (many keV) and their linear separation by the ion charge number \( Z \) at higher powers than MW.

Numerical studies since around 1977 [2: Sect. 10] for plane geometry demonstrated how laser intensities above \( 10^{14} \) W/cm\(^2\) generated two plasma blocks with ion energies above keV,
one moving into the target and the other against the laser after few ps interaction, see Fig. 1 where deuterium ions reached velocities up to $10^9 \text{ cm/s}$ at after 1.5 ps interaction by intensities of $10^{18} \text{ W/cm}^2$.

![Graph showing electromagnetic energy density and velocity](image)

**Fig.1.** $10^{18} \text{ W/cm}^2$ neodymium laser incident from the right hand side on an initially 100 eV hot very low reflecting bi-Raleigh plasma profile [2: Fig. 10.17] showing after 1.5 ps interaction the electromagnetic energy density (2) after the dynamic development had accelerated the plasma density to the velocities with a block moving against the laser and another into the plasma [2: Sect. 10].

2. Experiments with ps laser pulses
Laser driven plasma profiles of Fig. 1 never turned out, not only because such intense and very short laser pulses were not available, but much more due to the fact that relativistic self-focusing [4] which always destroyed the conditions of plane geometry and led to wave length diameter beams with extreme laser intensities accelerating highly charged ions to more than 100 MeV [2: Sect. 12] energy. The first and unique exception was the measurement by Sauerbrey [5] where he accelerated well defined plane plasma fronts with TW-0.3ps laser pulses. The observed acceleration of $10^{20} \text{ cm/s}^2$ was precisely reproduced by the theory of nonlinear force acceleration [6]. The measurements of Sauerbrey [5] were exceptional and an anomaly never observed before, because the laser pulses had an extreme suppression of prepulses (contrast ratio of at least $10^8$). This is the reason why no plasma plume was before the target which is necessary for relativistic self-focusing.

The crucial effect of the prepulse was then demonstrated in the experiments by Zhang et al [7] where TW-ps laser pulses in targets did not lead to the usually (relativistic self-focusing produced) extremely high x-ray emission as in all the other experiments but in very low x-ray emission. Irradiating a similar ps pulse of less intensity at times $t^*$ before the main pulse, did not change the x-ray emission until $t^*$ reached 70ps. This was exactly the amount of time needed to generate the plasma plume for relativistic self-focusing showing then the very high x-ray emission as usual.
A further crucial experiment for the anomaly was that by Badziak et al [8] measuring the energy $e_i$ of the ions emitted against the laser light from a copper target. Instead of the usually expected 22 MeV $\text{Cu}^{11+}$-ions they had only 0.5 MeV energy only and – what was significant and essential for clarifying the anomaly – the ion number did not change by thirty times varying laser power. Remembering the facts of above section 1., an explanation was again [9] based on avoiding relativistic self-focusing confirmed later in many experimental and numerical details [10,11]. A special proof was the directivity of the emitted ions. The constant number of accelerated ions was due to the fact that the skin layer of interaction was of optical nature and not determined by nonlinear effects, resulting nearly in an intensity independent skin depth. This is then a nonlinear force driven skin layer acceleration clarifying in retrospect [6] the observations by Sauerbrey [5] and Zhang et al. [7].

![Fig. 2 Driving a sphere of initially bi-Raleigh DT density profile by the nonlinear force, similar to Fig. 1, should result in an ablation (expansion) with 50% efficiency for driving the plasma implosion [14].](image)

**3. Ten times higher ablation efficiency at plasma compression for fusion**

When using gas dynamic ablation for the laser irradiated plasma corona for compressing the plasma interior to very high densities for controlled thermonuclear fusion, the hydrodynamic efficiency is very low, realistically only 5% while 95% of the energy of the laser pulse goes into the ablation of the plasma corona. The contrary can be achieved if the ablation is driven by the nonlinear forces as shown in Fig. 1. The nonlinear force converts practically all laser energy into directed kinetic energy of motion of low temperature plasma blocks at laser intensities near $10^{18}$ W/cm$^2$ by selecting specific initial density profiles achieving an ablation efficiency of 50%. The transfer of optical radiation into plasma motion, expressed as a nonlinear collisionless absorption could be solved as a rare case by an analytical solution of a nonlinear integral equation (by one of the authors: H.H.) and evaluated in a thesis [11]. It should be noted that the very high efficiency of collisionless absorption was based on the results of Fig. 1 and similar cases [2] while evaluations of the present available experiments [8,9,10] resulted in different gains according to varied conditions though this was sufficient for distinguishing from Wilks’ TNSA process (see [10]).

The skin layer is rather thin in the nonlinear force accelerated plasma blocks though it was important to note [6,9] that their space charge neutral ion current densities are exceeding $10^{11}$
Amp/cm², which value is sufficient for generation of a fusion flame in low compressed DT fuel [12]. In order to arrive at thicker plasma blocks, a conical geometry was considered [6] where even higher than solid-state densities of the very massive high velocity and low temperature directed plasma blocks can be produced for the irradiation of the DT fuel similar to ignition of low compression DT with laser produced 5 MeV electron beams [13]. This case considers the thermonuclear burn “into large masses of much lower density DT” including values of 12 times the solid state (“3g/cm³”) or less. DT fusion at low compression or even at the solid state [12] was never excluded though initially considered as “not practical” [14]. The fundamentally new situation with the PW-ps laser pulses may open the practicality of igniting low compression DT fuel with the modification of the fast igniter [15] using the Nuckolls-Wood scheme with electron beam ignition [13], or with the higher than 10¹¹Amps/cm² plasma blocks [16] where automatically some higher than solid density DT is involved.

Alternatively to the generation of the fusion flame [12,16], the block generation as shown in Fig. 1 may be used for an earlier discussed concept [17] of laser fusion as shown in Fig. 2. Using of a spherical DT plasma shell of solid density similar to that with a bi-Rayleigh initial density profile of Fig. 2 to be irradiated uniformly by a laser pulse not much below the relativistic threshold in the range of ps duration, conditions were evaluated for the compressed plasma how volume ignition [18] will lead to a total fusion gain (per energy of the incident laser pulse) of 200 by using a MJ-3ps laser pulse in an initial solid DT shell of 3.27 cm radius. The advantage is then the high ablation efficiency at these laser intensities. It should be noted that the direction (k-vector) of the laser radiation at the shell does not need to be exact radial, as was shown from the general theory [1,2]. Only the orbital distribution of the laser intensity and their synchronization has to be of a very high quality.

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