Laser and Particle Beams (2005), *23*, 441–451. Printed in the USA.
Copyright © 2005 Cambridge University Press 0263-0346/05 $16.00
DOI: 10.1017/S0263034605050627

Difference between relativistic petawatt-picosecond laser-plasma interaction and subrelativistic plasma-block generation

HEINRICH HORA
Department of Theoretical Physics, University of New South Wales, Sydney, Australia

(Received 1 January 2005; Accepted 8 March 2005)

Abstract

Some preliminary views are presented to the topic "Fast High Density Plasma Blocks Driven by Picosecond Terawatt Lasers" of the UWS-International Workshop 1–4 December 2004 in Sydney, Australia, underlining the motivation to explain the difference between the relativistic and the subrelativistic effects of ps-laser pulse interaction with plasma at powers above TW. This refers to specifically selected experimental and theoretical presentations at the workshop containing results for explaining the differences but also the important applications for studies on the fast ignitor scheme for application on nuclear fusion energy. One of the aims with relativistic proton beams is to realize conditions of spark ignition, while the subrelativistic case implies the generation of fast plasma blocks eventually with the possibility to ignite a fusion flame in uncompressed solid DT fuel for a power station with high efficiency.

Keywords: Debye lager fields; Ion highly charged; Laser plasma interaction; Nonlinear forces; Particle-in-cell (PIC); Ponderomotion; Relativistic laser effects; Skin layer acceleration

1. INTRODUCTION

A new era in laser-plasma interaction was opened with the advent of petawatt-picosecond laser pulses (Perry & Mourou, 1994; Mourou & Tajima, 2002) based on the chirped pulse amplification (CPA) discovered by Mourou, or excimer lasers (Schäfer, 1986; Teubner *et al.*, 1993) which applications are stimulating numerous fields. These are:

- the laser generation of energetic, highly charged ions for sources in accelerators (Haseroth & Hora, 1996), or for ion implantation (Boody *et al.*, 1996; Sari *et al.*, 2005),
- the tabletop electron beam generators (Hora *et al.*, 2000; Hartemann *et al.*, 1998),
- the broad stream research for gaining clean, safe, unlimited, and low-cost energy from nuclear fusion in the future (see following Section 2),
- for basic physics that is, by zetawatt laser pulses (Mourou & Tajima, 2002) where
- pair production in vacuum (Hora, 1975) or Hawkings–Unruh radiation with accelerations as at the surface of black holes (Hora *et al.*, 2002) may be achieved.

The results by Badziak *et al.* (2003) showing fast blocks of plasma moving like pancakes with very slow lateral expansion against the laser light, seem to be following the scheme of an unexpected skin-layer interaction (Hora *et al.*, 2002; Hora, 2003) which can be used as ion beams with orders of magnitudes better than all the earlier known ion beam sources for filling accelerators, it has to be understood that the classical laser ion sources had an enormous advantage over the standard ion sources like ECR etc. (Haseroth & Hora, 1996) by orders of magnitude. Since the ps laser sources are very reliably working in pulsed sequence up to 100 Hz and higher, this should permit a drastic improvement in the capacity of very large accelerators, as, e.g., the design of the successor to the LHC at CERN where planning is on the way (Thomas, 2004). As general interest, the new developments are now devoted to high energy density physics (HEDP) studies (Campbell, 1992; Campbell *et al.*, 1997).

As a kind of introduction and overview to the topics of this workshop, the following summarizes some aspects of fusion energy (Section 2) as the main interest for the application of ps laser pulses with powers of TW and more. The gathering of experts at the workshop was aimed at clarify

---

Address correspondence and reprint requests to: H. Hora, Department of Theoretical Physics, University of New South Wales, Sydney 2052, Australia. E-mail: h.hora@unsw.edu.au

the differences of complex relativistic phenomena usually observed at these interactions versus subrelativistic phenomena first observed from ion emission by Badziak *et al.* (1999), and studied intensively after this unique phenomenon was recognized as a skin layer acceleration (SLA) dominated by the nonlinear (ponderomotive) force (Hora *et al.*, 2002). It was essential that any prepulse be carefully suppressed since it was discovered from X-ray emission measurements by Zhang *et al.* (1998), and is a condition to avoid (Hora & Wang, 2001), relativistic self-focusing (Hora, 1975; Jones *et al.*, 1982; Häuser *et al.*, 1992; Esarey *et al.*, 1997; Osman *et al.*, 1999, 2004*a*) which is usually occurring (Hora, 1991, 2000; Haseroth & Hora, 1996) as confirmed by numerous experiments. In order to prepare for the difference of the theoretical methods (hydrodynamics versus particle in cell (PIC)), Section 3 is following. Section 4 is then summarizing some significant points.

2. FUSION ENERGY

In order to gain safe, clean, unlimited, and very low cost energy from nuclear fusion of Deuterium (D) and Tritium (T) or other light nuclear reactions, these are extensively studied. These reactions were a fully unexpected process occurring at collisions between nuclei at 10 keV energy or even less because the usual collision energy for reacting nuclei is above MeV in order to overcome the Coulomb repulsion, and to get the colliding nuclei into the distance close to their diameter of femtometers. It was the fully unexpected discovery of Cockroft *et al.* (1933) and Oliphant *et al.* (1934) that DD reactions occurred at distances 100 times larger than the nuclear size. These fusion reactions cannot be simply explained by Gamov factors which would be much less than 10^{-40} and a resonance processes was generally suggested, but a consequent theory was not available until the work by Li *et al.* (2000, 2004) for the DT reaction and for the DD, and other reactions to reproduce the cross sections in highly accurate agreement with measurements based on a transparent model with a Schrödinger potential having an imaginary part. Before, only numerical fitting, e.g., with five numerical factors (Clark *et al.*, 1978) or similar were available for reproducing the measured cross sections.

These hot fusion reactions at particle energies in the scale of 10^4 eV (about 100 Million Kelvin) are of interest for fusion power stations in the future. Most investment in research during the past 50 years went to the ITER magnetic confinement reactor proposal which—if it would be decided next to be built for about $10 Billion—should by 2015 produce discharges of 1000 seconds duration producing 500 MW fusion energy from an input of 500 MW electrical energy (Hora, 2004). This corresponds to a gain of electrical energy per input energy of 0.3 only. One of the key problems not yet solved is the wall erosion needing a replacement of the wall every one to two years. An alternative was opened since the discovery of the laser to be used for driving fusion reactions. Fusion neutrons were measured since 1968–1969 (Hora, 1991). The biggest lasers, NIF and LMJ, being half finished are to demonstrate ignition by about 2010. For laser fusion based on volume ignition (Hora & Ray, 1978), these type of lasers with 5 MJ-nanosecond pulses and compression to twice the measured values of 2000 times the solid state (Azechi *et al.*, 1991) may reach 120 times fusion energy per total electric energy input, i.e., a gain of electricity per input energy of about 30 (Hora *et al.*, 2003, see Miley *et al.*, 2005; Osman *et al.*, 2005). Facilities like NIF or LMJ need an enormous reduction in size, costs, and improvement e.g., in laser pulse repetition, but basically there may not be a physics limit for such developments.

In contrast to this scheme with 10 MJ-ns laser pulses, solidly based on present achievements, an alternative for laser fusion may be possible to be explored now by using the new developments of petawatt-picosecond laser pulses (Perry & Mourou, 1994) to aim the "fast ignitor" (Tabak *et al.*, 1994). This was initiated by Campbell *et al.*(2000) (Osman *et al.*, 2005) when he realized from the measurements of Azechi *et al.* (1991) since about 1985 that the laser compression of a carbon polymer was well reaching the density of 2000 $\mathrm{g/cm^3}$ (about 2000 times the solid state) but the temperature was unexpectedly low, only about 3 Million Kelvin. In order to reach fusion, Campbell *et al.* (2000) envisaged that the addition of the necessary heating by depositing kJ energy from a ps pulse to the center of DT, compressed to 3000 times the solid state should result in very high gain fusion energy. This scheme has reached interesting neutron gains (Hora *et al.*, 1998; Kodama & Fast Ingitor Consortium, 2002) and wide range studies are on the way.

The difficulties in these fast ignitor studies consist in the fact that the ps laser pulses with powers above TW resulted in numerous unexpected relativistic effects and an estimation of such effects may (instead of reaching spark ignition) lead to volume ignition (Hora *et al.*, 1998). One remarkable alternative is the use of peripheral ignition of a highly precompressed plasma (Hain & Mulser, 2001; Mulser & Bauer, 2004; Mulser & Schneider, 2004; Deutsch, 2004) or the generation of very high density 5 MeV electron beams from petawatt irradiation of a high density precompressed DT plasma, where the electron beam will ignite a controlled fusion reaction wave in a large amount of nearly uncompressed DT fuel producing a very high gain (Nuckolls & Wood, 2002).

It was an early attempt for laser fusion (Bobin, 1971; Chu, 1972) to consider the ignition of a fusion reaction wave front in uncompressed DT by a laser or particle beam pulse, Figure 1. It turned out that the following conditions A and B had to be fulfilled if light DT ion beams of the optimum energy of 80 keV (at the maximum cross section for resonance, Li *et al.* (2000)) are incident on solid state DT: the ion current density, j, had to be at least (Bobin, 1971, 1974: Table I; Brueckner & Jorna, 1974)

$$j > j^* = 10^{10}\ \mathrm{Amps/cm^2} \quad \text{condition A} \tag{1}$$

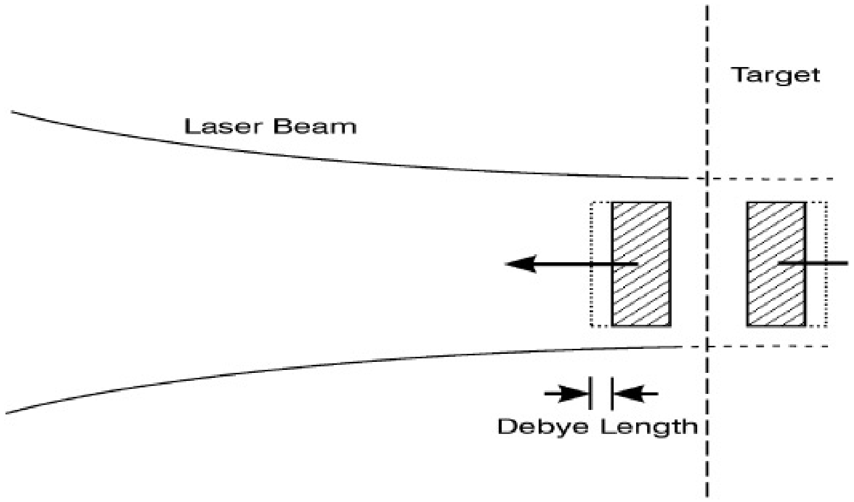

Fig. 1. Fusion scheme where a laser beam irradiates solid DT producing a block of plasma moving against the laser light and another block moving into the target. Ignition requires extremely high DT current densities and energy fluxes of the blocks, Eqs. (1) and (2).

and the energy flux density E had to be larger than E^*

$$E > E^* = 4 \times 10^8 \text{ J/cm}^2 \quad \text{condition B.} \tag{2}$$

These values were completely out of reach for ion beams in the 1970s though a relaxation of the condition can be expected due to collective effects (Gabor, 1953) by interpenetration (Hora, 1983). However, after the experiments of Badziak *et al*. (1999, 2003, 2004*a*, 2004*b*) and the theory of the skin layer acceleration (Hora *et al*., 2002; Hora, 2003; Miley *et al*., 2003, 2004; Osman *et al*., 2004*a*, 2004*b*; Hora, 2004), the ps laser pulses in the TW to few PW range may provide the conditions A and B as explained in Section 4.

3. DISTINGUISHING RELATIVISTIC FROM SUBRELATIVISTIC TW-PS LASER-PLASMA INTERACTION

The theoretical description of laser-plasma interaction (Hora, 1991, Sections 2 to 4) depends on the conditions of the plasma whether the following models can be applied:

a. single particle motion by following up the differential equation of motion for N (one million or more) single electrons and ions;
b. kinetic theory by working with a distribution function depending on the time dependent number of particles within the phase volume $d^3 \times d^3v$ in space and velocity leading to a Boltzmann or Vlasov equation;
c. hydrodynamic motion of the plasma as a net (quasi space-charge free fluid for electron and ions) or the genuine two-fluid model for the electrons and ion separately including the strong electrostatic fields between them.

Method (a) (Kruer, 1988) arrives at the most general description of numerous effects especially where no thermal equilibrium is reached between the particles but where the limitations even of the largest available computers does not permit the general inclusion of the long range Coulomb forces for collisions and the exchange mechanisms for reaching or going to reach thermal equilibrium. Method (b) again was very successful but not as general by lost of information to describe numerous plasma phenomena simplifying methods a, however without a complete cover of the collisions, since the Boltzmann collision term has not yet been discovered apart from approximations. Hydrodynamics (c) can explain many phenomena including complete inclusion of collisions covering equi-partition and transport processes but based on quasi thermal equilibrium conditions of the fluids only.

One advantage is the development of method (a) to combine with method (b) as the particle in cell (PIC) technique for a more economic and efficient single-particle description including phase space as successfully used in laser-plasma interaction (Wilks *et al.*, 1992) however still not directly covering collisions. One precondition for the hydrodynamics is that the Debye length is sufficiently short compared with the grids in the hydrodynamics. If this is not the case, the collisionless description of the single particle motion and the macroscopic electric fields between the particles is the domain of the PIC method. In the PW-ps laser plasma interaction both methods, hydrodynamics and PIC are to be separated from case to case but there are examples also where there is a rather good agreements between the results of both methods.

A strong relativistic effect was self-focusing which general formulation (Hora, 1975) producing very highly charged ions of up to few hundred MeV energy in full agreement with the theory (Hora, 1991, 2000) was working even at laser intensities up to 1000 times lower values than the relativistic threshold intensity I_{rel} where the quiver energy is mc^2 (in cgs units)

$$
\begin{aligned}
I_{rel} &= 1.5(mc\omega/e)^2/377 \\
&= 4.08 \times 10^{18}/\lambda^2 \text{ W/cm}^2 \text{ (wave length } \lambda \text{ in } \mu\text{m)} \qquad (3)
\end{aligned}
$$

For the subrelativistic approximation, the relativistic self-focusing was derived by several authors with the same result (Hora, 1991). For the subrelativistic and relativistic range (Hora, 1975, 2003), Figure 2, a plane wave front Gaussian laser beam hitting uniform plasma shrinks to a diameter of $\delta\lambda$ because the relativistic change of the mass of the quivering electron has a shorter effective wave length at higher laser than at lower laser intensity. If the Debye length is less than 0.1,λ, the energy ε_i of Z times charged ions is

$$
\begin{aligned}
\varepsilon_{trans} &= Zmc^2Pe^2/(\pi^2\delta^2m^2c^5) \\
&= Zmc^2(P/\delta^2)5.7 \times 10^{-12} \text{ eV} \qquad (4)
\end{aligned}
$$

where the laser power P is in Watts and the beam diameter δ is in multiples of the wave length (between 0.6 and 1). One example is that 13 times ionized copper achieves about 22 MeV energy with a laser power of 0.5 TW as observed under usual conditions of relativistic self focusing. The ions are accelerated at the origin by the nonlinear (ponderomotive) force nearly spherically symmetric with a small deviation as explained (Häuser *et al.*, 1992), but appear with a wide cone against the laser light due to slowing down in the target. The measured number of these fast ions from relativistic self-focusing per interaction is 10^{14} or more in agreement with the theory.

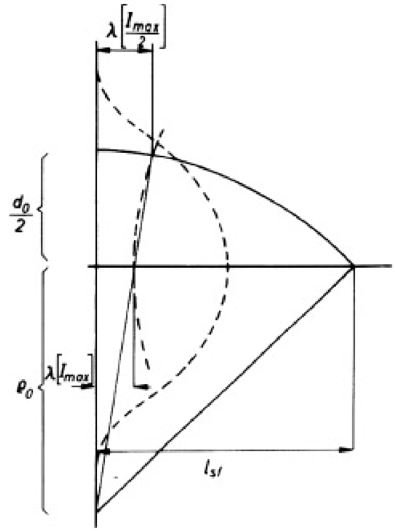

Fig. 2. Relativistic self-focusing of a laser beam of radius $d_o/2$ of Gaussian intensity profile hits a plane plasma surface. Due to relativistic mass change of the quivering electron, the effective wave length is shorter at central highest laser intensity than outside causing the bending of the plane wave front until the beam receives the diffraction limited diameter of about a wave length (Hora, 1975).

The emission of fast ions in laser produced plasmas was of interest from early research as far as only laser pulses of less than MW power produced classical plasma heated thermal ion emission in the 10 eV range. At higher powers, the 10 keV ions were due to ponderomotive self-focusing (Hora, 1969, 1991), while the measurements of Ehler (1975) showed three groups of ions, the Z-separated fast group following relativistic self-focusing and subsequent nonlinear (pondermotive) force acceleration, a second fast Z-separated group and the third group of thermal emitted plasma as seen in many repeated experiments later (Woryna *et al.*, 2000; Wolowski *et al.*, 2002, 2003). There is also a Z-separated ion group from ambipolar separated ions from the thermal plasma surface processes (Wägli & Donaldson, 1978) where the number of ions is so small that this group usually is not detected. The second fast group (Ehler, 1975; Woryna *et al.*, 2000) is clearly the result of ambipolar acceleration of the hot X-ray group according to Gitomer *et al.* (1986), where the energetic quivering electrons are etherealized—confirming anomalous resistively expressed a quantum modified collisions (Haseroth & Hora, 1996)—with subsequent ambipolar acceleration (Hora, 2003).

Within this rather complex situation, the ps-TW interaction produces a further complexity due to the mentioned conditions that the Debye length can be too large for applying the mentioned models and PIC (Wilks *et al.*, 1992; Shorokhov & Pukhov, 2004; Greschik & Kull, 2004) or other methods need to be applied.

The first significant measurement was that with 30 TW, 400 fs laser pulses (Umstadter, 1996) where 10^8 electrons of 30 MeV energy were emitted within a cone. This was in contrast to the beat-wave and wakefield accelerations (Balakirev *et al.*, 2004) where the acceleration (Kitagawa *et al.*, 1992) did not result in the expected large number of accelerated electrons. The mechanism in the case of the Umstadter experiment was obviously that there was a ponderomotive acceleration of free electrons (Häuser *et al.*, 1994; Wang *et al.*, 1998; Lefebvre *et al.*, 1998; Hartemann *et al.*, 1998; Malka & Fritzler, 2004) confirming the 30 MeV electrons and the angle of the emission cone (Hora *et al.*, 2000) while the number of electrons was reproduced by the volume of relativistic self-focusing which for the 400 fs was applicable because of the short range of mechanical motion during this period.

The measurements after that of Umstadter (1996) with ps or shorter laser pulses of TW to PW power showed then a rich field of relativistic effects (Roth *et al.*, 2001; Schwoerer *et al.*, 2001; Hoffmann *et al.*, 2005) with pair production, gamma radiation for subsequent nuclear transmutations (Ledingham *et al.*, 2000; Magill *et al.*, 2003), ions with nearly GeV energy (Clark *et al.*, 2001) analyzed as different group processes (Hora, 2003) and alternative electron acceleration mechanisms up to GeV energy. The explanation of the measured 5 MeV proton beams (Roth *et al.*, 2000, 2001; Osman *et al.*, 2004*a*; Hoffmann *et al.*, 2005) by a target normal sheath acceleration mechanisms (TNSA) was derived from PIC computations (Wilks *et al.*, 2001). PIC computations for 10^{24} W/cm^2 laser intensities arrived at the nonlinear force acceleration of plasma blocks (Esirkepov *et al.*, 2004) easily covering the conditions on how to ignite uncompressed solid state density DT fusion fuel, Eqs. (1) and (2).

Within these numerous new aspects, it seems to be a drastic alternative, how the subrelativistic interaction occurs as a skin layer acceleration (SLA) mechanism detailed evaluated experimentally from ion emission (Badziak *et al.*, 1999, 2003, 2004*a*) and recognized as the skin layer process (Hora & Wang, 2001; Hora *et al.*, 2002; Hora, 2003) after the importance of the prepulse was known (Zhang *et al.*, 1998) for avoiding relativistic self focusing and as seen before from the KrF ps-TW interaction with ideal plane geometry nonlinear force acceleration (Sauerbrey, 1996). This all was reproduced from numerical simulations with the then fully permitted genuine two fluid computations (Badziak *et al.*, 2004*a*, 2004*b*; Cang *et al.*, 2005).

PIC is now a broad stream development (Wilks *et al.*, 1992, 2001; Esirkepov *et al.*, 2004) not only for exploring the relativistic effects of PW-ps laser plasma interaction. The whole physics of high electric fields (Hartemann, 2002)—initially derived from the electron acceleration by lasers in vacuum (Hora, 1988; Scheid & Hora, 1989; Häuser *et al.*, 1994; Hartemann *et al.*, 1998)—opens a new development in physics. The properties of the double layer on all laser produced plasmas expanding into vacuum characterized by a Debye length are the essential mechanism for Wilks' (Wilks *et al.*, 2001) TNSA proton acceleration. This is the reason why these double layers produce surface tension (Hora *et al.*, 1984; Eliezer & Hora, 1989) surface tension in plasmas and produce a stabilization of surface waves working against Rayleigh–Taylor instabilities, a result which has not been exhausted by theory which always results in worse instabilities than measured. Generalizing this to the electrons in metal by using their Fermi energy instead of a temperature in the Debye length results the double layer expressing the work function of metals and offering a consequent quantum theory of surface tension and surface energy as measured (Hora *et al.*, 1989). Generalizing this to the hadrons of nuclei, results in a theory of the forces, confining a nucleus at the well known diameters, and the transition into quark-gluon plasmas (Hora *et al.*, 2005). This affinity to the TNSA model is the reason why these questions were discussed in this connection (Osman *et al.*, 2005).

4. INITIAL DEVELOPMENT OF SUBRELATIVISTIC PLASMA BLOCK GENERATION

It was one of the main motivations for the UWS International Workshop "Fast high Density Plasma Blocks Driven by Picosecond Terawatt Lasers" to clarify the differences between the relativistic and subrelativistic laser-plasma interaction in this range as explicitly outlined by presented contributions. It seems to be indicated to summarize the following background facts for underlining the skin layer acceleration (SLA) process.

For understanding the skin layer laser plasma interaction theory with plane waves geometry we explain the nonlinear (ponderomotive) force as the main driving process in the following numerical results The force density in plasmas (Hora, 1991) $\mathbf{f} = \mathbf{f}_{\text{th}} + \mathbf{f}_{NL}$ consisting in the thermokinetic force $\mathbf{f}_{\text{th}} = -\nabla p$ given by the gas dynamic pressure p and the general transient (Hora, 1985) nonlinear force

$$\begin{aligned}\mathbf{f}_{NL} = \nabla\cdot[&\mathbf{EE} + \mathbf{HH} - 0.5(\mathbf{E}^2 + \mathbf{H}^2)1\\ &+ (1 + (\partial/\partial t)/\omega)(\mathbf{n}^2 - 1)\mathbf{EE}]/(4\pi)\\ &- (\partial/\partial t)\mathbf{E}\times\mathbf{H}/(4\pi c),\end{aligned} \tag{5}$$

where 1 is the unity tensor, ω the laser frequency, and $\mathbf{n}$ is the (complex) refractive index. This can be reformulated into

$$\begin{aligned}\mathbf{f}_{NL} = \mathbf{j}\times\mathbf{H}/c &+ \mathbf{E}\rho + \mathbf{P}\cdot\nabla\mathbf{E}/4\pi\\ &+ (1/\omega)(\partial/\partial t)\mathbf{E}\nabla\cdot(\mathbf{n}^2 - 1)\mathbf{E}/4\pi\\ &+ [1 + (1/\omega)\partial/\partial t](\mathbf{n}^2 - 1)\mathbf{E}\cdot\nabla\mathbf{E}/4\pi.\end{aligned} \tag{6}$$

It was shown that these algebraically identical formulations are Lorentz and gauge invariant and are the complete description of the force density in the plasma due to electric and magnetic fields. The formulation (5) is that of the Maxwellian stress tensor including the dielectric response and transient (time dependent) behavior of the fields. The formulation (6) explains the parts acting in the nonlinear force. Here one recognizes on the right-hand side first the Lorentz term $\mathbf{f}_{\text{Lorentz}} = \mathbf{j}\times\mathbf{H}/c$ with the plasma current density $\mathbf{j}$ and the vacuum velocity of light c, then the Coulomb term $\mathbf{E}\rho$ with the electric charge density ρ and as the third term the Kelvin ponderomotive term (Hora, 2000, see Eq. (1))

$$\begin{aligned}\mathbf{f}_{\text{Kelvin}} = \mathbf{P}\cdot\nabla\mathbf{E}/4\pi &= (\mathbf{n}^2 - 1)\nabla\mathbf{E}^2/8\pi\\ &- (\mathbf{n}^2 - 1)\mathbf{E}\times(\nabla\times\mathbf{E})/4\pi.\end{aligned} \tag{7}$$

The remaining terms in Eq. (6) are new nonlinear terms which were derived for the general equation of motion in plasmas from the studies of laser interaction. The proof for the final generality of Eq. (6) was given by momentum conservation for the nontransient case ($\partial/\partial t = 0$) and for the transient case by symmetry (Hora *et al.*, 1984) of the terms and from gauge and Lorentz invariance.

For the correct interpretation it is necessary to mention that Kelvin's ponderomotive force is identical with the nonlinear Schlüter term

$$\mathbf{j}\cdot\nabla(1/n_e)\mathbf{j}m/e^2 = (\omega_p^2/\omega^2)\mathbf{E}\cdot\nabla\mathbf{E}/4\pi, \tag{8}$$

remembering the definition of the electric polarization **P** and the refractive index without collisions

$$\mathbf{P} = (\mathbf{n}^2 - 1)\mathbf{E}/4\pi. \tag{9}$$

From Kelvin's ponderomotive force (7) follows formally an expression of the "field gradient force" or the electrostriction for collisionless plasma (**n** without imaginary part)

$$\mathbf{f}_{NL} = (\mathbf{n}^2 - 1)\nabla\mathbf{E}^2/(8\pi). \tag{10}$$

This can be used for the case of perpendicular incidence of plane laser waves on an inhomogeneous plasma of one-dimensional geometry e.g., along the coordinate x. For the same conditions, the stress tensor description produces a force density into the x-direction of

$$f_{NL} = -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi). \tag{11}$$

Formulation (10) led to the common expression of "ponderomotive force" for (1). As is known for (plane wave) perpendicular incidence of laser radiation on plasma, the Schlüter term is then zero. Nevertheless there is a force of the form of Eq. (10). In this case, however, the nonlinear force $\mathbf{f}_{NL}$ is the result of the Lorentz term in Eq. (6). This confusion of the definitions is avoided if one uses the general expression of the nonlinear force (6) for the electrodynamic part of the force density in plasma. This is valid for any incidence, for plasma with collisions, and including time dependence of the fields.

The nonlinear force (5) or (6) was the first inclusion of the dielectric plasma properties into the electrodynamic interaction of (laser) fields with plasma where the first step was for the simplified case of perpendicular incidence while the ponderomotive interaction of electromagnetic waves on free electrons without dielectric effects for plasma confinement was discussed before (Weibel, Kibble, and others, see Hora, 1991). The proof that (5) and (6) are the general solution for the non-transient (stationary laser) case ($\partial/\partial t = 0$) was given from momentum conservation for the collisionless case where nonlinear terms were derived as necessary addition for completion of Schlüter's two-fluid equation of motion leading to the general transient case (Hora, 1985).

The action of the nonlinear force at the plane wave geometry can be seen as shown in Figure 4-1 of Hora (2000). An electromagnetic wave incident from vacuum for $x > 0$ on a plasma with (initially) monotonous increase of electron density $n_e(x)$ from $x = 0$ will cause an increase of the electromagnetic field energy density $(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi)$ up to a maximum close before the density reaches the value of the critical electron density n_{ec} (where the plasma frequency $\omega_p = (4\pi e^2 n_e/m)^{1/2}$ is equal to the laser frequency ω). For further increasing x, the energy density will exponentially drop to zero in the overdense plasma ($\omega_p > \omega$) within the skin depth similar to metal optics due to the plasma collisions. The negative gradient of the energy density results in the nonlinear force (11) driving the plasma corona as a whole blocks (John Nuckolls said like gravitation) toward the vacuum. The plasma block between the maximum of the energy density and its vanishing value in the skin layer is driven into the plasma interior. This is identical with the result of the dielectric increase of the electric field $|\mathbf{E}| = E_v/|n|^{1/2}$ expressed by its vacuum amplitude E_v and the oscillating cos-function of the wave in the inhomogeneous plasma.

Numerical cases of the real plasma dynamics with nonlinear plasma collisions and numerically detailed wave optical calculations of the laser field for each time step during the time dependent variation of the plasma density and temperature were performed for neodymium glass laser intensities between 10^{14} and 10^{18} W/cm^2 for times up to few ps using a single fluid hydrodynamic code (see Figs. 4-13 to 4-16 in Hora, 2000). Within this short time, velocities of the Deuterium plasma blocks of up to nearly 10^9 cm/s resulted. An example for plasma of initially double-Rayleigh profile of 100 μm thickness corresponding to 95 vacuum laser wave lengths (Fig. 10.17 in Hora, 1991) for minimizing initial optical reflection for Deuterium plasma with central maximum density very close to the critical density and an initial temperature of 100 eV is shown in Figure 3. Irradiating 10^{18} W/cm^2 neodymium glass laser radiation from the right-hand side, we see after 1.5 ps that the light does not penetrate up to the maximum initial density at x = 0 but only to about 37 μm due to the (weak) collision absorption shown from the spatial distribution of the electromagnetic energy density $(\mathbf{E}^2 + \mathbf{H}^2)/8\pi$. This energy density as negative gradient produces the forces, Eq. (11), to move a block of Deuterium plasma between 40 and 63 μm against the laser light with velocities of up to 10^9 cm/s, while a block of plasma of similar thickness is moving with velocities up to 3×10^8 cm/s toward the plasma interior. The initial conditions were chosen in such a way that the block motion was possible until the irradiation time of 1.5 ps. At later times or for other initial conditions, the generation of locally reflected waves in the dynamically developing laser field within the driven and thermally expanding plasma causes the well known driving of plasma into the nodes of the partially standing wave field disturbing the smooth motion of the blocks, see Fig. 10.20a of Hora (1991). These calculations were more than 20 years too early in view of the PW-fs laser pulses of today.

What was significant about the anomaly of ion emission observed by Badziak *et al.* (1999) is the measurement of very low maximum ion energies and subsequent measurements which were done after the skin layer model (Hora *et al.*, 2002) were confirmed (Badziak *et al.*, 2003, 2004*a*,

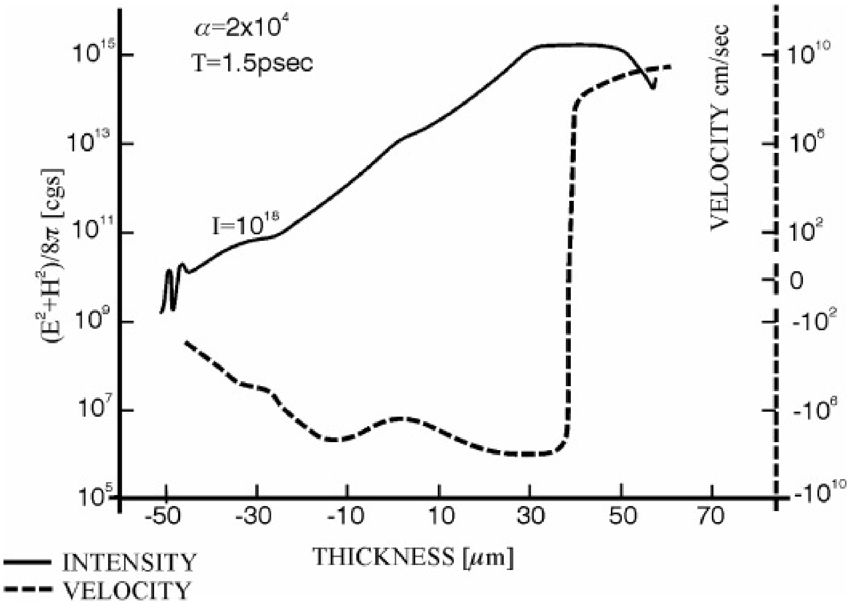

Fig. 3. Generation of blocks of Deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100 eV hot and 100 μm thick bi-Rayleigh profile (Fig. 19.17 of Ref. Hora, 1991) with minimum internal reflection. The electromagnetic energy density $(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi)$ is shown at the same time of 1.5 ps after begin of the constant irradiation.

2004*b*). Focusing a neodymium glass laser pulse of 1.5 ps duration at power P up to 2.1×10^{11} W produced Cu^{+13} ion or up to 450 keV energy. Using the theory of relativistic self focusing, Eq. (4), the ion energy after the usual relativistic self-focusing should have been 22.6 MeV. This was a first indication that relativistic self focusing could not have occurred in this experiment. It is important to note that any prepulse (aspect ratio) was suppressed by a factor 10^8. Another very strange result is that not any change of the number of the fast ions (to distinguish from the following slow thermal ions) was observed on the variation of the laser power (energy) over a factor 25 (Fig. 4) while the ion velocity increased on a square root law such that the energy of the fastest ions showed the following dependence on the laser intensity I

$$\varepsilon_{imax} = const \times I. \qquad (14)$$

Therefore, the measured fast ions were different from the quiver-collision property (Hora, 2003) but were different also from the relativistic-self-focusing property due to the 50-times too low maximum ion energy. Later, after knowing the skin layer interaction (Hora *et al.*, 2002*a*, 2002*b*), measurements were performed (Badziak *et al.*, 2004*a*, 2004*b*, 2005) in order to clarify this discrepancy specifically designed for these conditions using the laser system described before. This neodymium glass laser system produced 0.5 ns laser pulses of 1.4×10^9 W/cm^2 in the focus for irradiation on gold targets at an intensity of 2×10^{14} W/cm^2. In other measurements with the same focus geometry and the same pulse has been compressed to 1.2 ps for a power of $P = 6 \times 10^{11}$ W for an intensity of 8×10^{16} W/cm^2 on the same gold target. For clarifying the discrepancy between ps and ns irradiation, the whole optical system was identical in both cases of experiments with a short or long pulses where the same laser energy of 0.7 J was incident in both cases. The energy of the emitted ions was measured by the time of flight probes and by ion electrostatic analyzers. A most significant result is that of a maximum ion energy of 0.95 MeV for Au^{+34} produced by the 0.5 ns pulses, while laser pulses of 1.2 ps duration produced fastest 1.03 MeV Au^{+26} ions.

How is it possible that the 30-times ionized gold ions had nearly the same maximum energy of MeV though the irradiation power and the intensity differed by more than 400 between the cases of 0.5 ns and 1.2 ps laser pulse duration? Interestingly the 0.5 ns case is close to the expected ion energy following the relativistic self focusing and nonlinear acceleration mode, Eq. (4), within a factor of about two where experimental error bars and minor simplifications of the model may be ignored when realizing the several hundred times different result for the ps-case. This also clearly confirms the enormous discrepancy in the preceding measurements (Badziak *et al.*, 1999) with the more than 50-times lower maximum ion energy for ps irradiation than with ns irradiation at the same intensities.

From the numerous details of the present measurements, one may mention also the result that maximum X-ray emission depending on the focusing distance from the gold target appeared for the 0.5 ns laser when the target was 280 μm moved away from the focus at vacuum conditions. This may be explained qualitatively as a plasma-optical process that the $<10^{11}$ W/cm^2 laser intensity beam hitting the pre-generated plasma was shrinking initially by pondero-

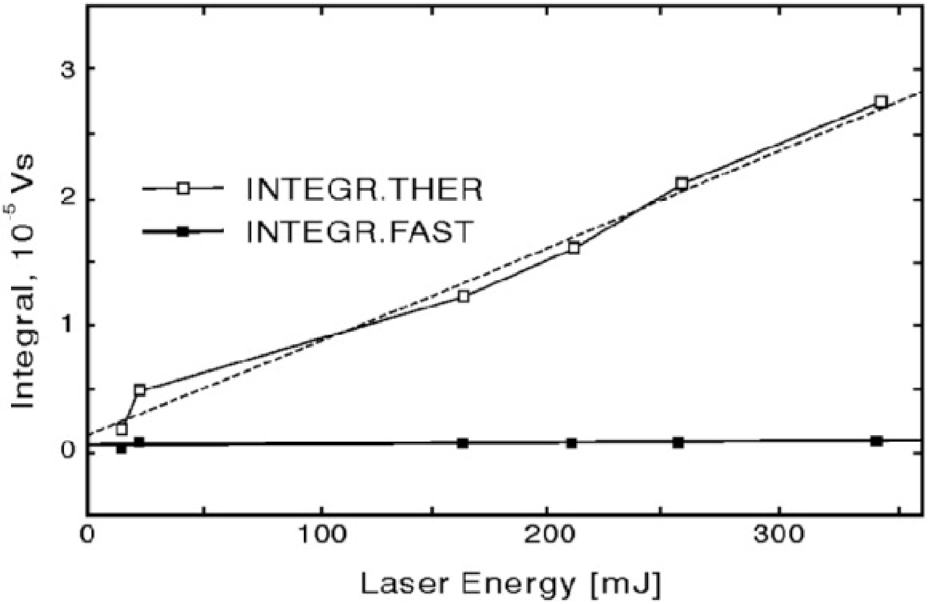

Fig. 4. Number of (integrated signal) emitted fast ions and thermal ions from a perpendicular irradiated copper target at neodymium glass irradiation for 1.2 ps pulses depending on the laser pulse energy focused to a 30 wavelength diameter beam at the target surface with suppression of a prepulse by 10^8 for a time less then 100 ps before the main pulse arrived. During the last 100 ps the contrast ratio was about 10^4 (Badziak *et al.*, 1999).

motive self focusing (Hora, 1969) within the sufficiently long time and when reaching the necessary minimum intensity for the relativistic self-focusing going to the diameter of about one wave length necessary for the nonlinear-force acceleration of the Au + 30 ions to the observed MeV energy as in all the numerous cases reported before. This all agrees with the measured slight decrease in the average energy of the thermal plasma on increasing laser intensity of the slow thermal group of plasma in the 0.5 ns case.

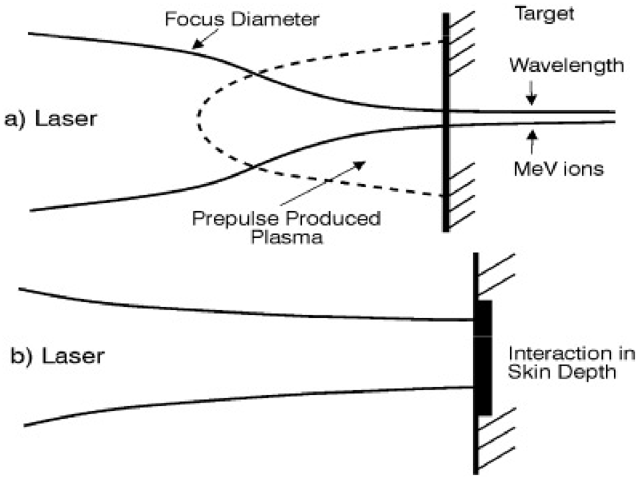

Fig. 5. Usual interaction of a laser pulse with a target in vacuum (**a**) where a pre-plasma is produced causing relativistic self-focusing with very high laser intensities in the beam squeezed to about one wave length diameter and subsequent very high energy ion emission. If relativistic self focusing is suppressed (**b**) by avoiding a pre-plasma at very high contrast ratio (suppression of pre-pulse), plane wave geometry nonlinear force acceleration of plasma blocks in the skin layer appears.

The uniqueness of the skin layer acceleration by the nonlinear force can be seen also from the direction of the emitted ions, see Figure 6 in Badziak *et al.* (2004*b*). As explained before, the ion acceleration by the nonlinear force after relativistic self focusing goes into all directions similar to the ambipolar acceleration in the hot electron mechanism (Gitomer *et al.*, 1986; Haseroth & Hora, 1996; Hora, 2003) as documented also in the just mentioned figure at ns laser pulse interaction. It there is no relativistic self-focusing and the plane geometry nonlinear force acceleration dominates in the skin layer, the plasma blocks move like pancakes against or with the laser beam with a little sidewise stretch. Exactly this was measured.

Summarizing, Figure 5 shows the essential difference between the skin layer acceleration due to suppression of prepulses, and the usual interaction with generation of a preplasma with subsequent relativistic self-focusing leading to the enormously high laser intensities and subsequent numerous relativistic effects.

REFERENCES

Azechi, H., Jitsuno, T., Kanabe, M., Mima, K., Miyanaga, N, Nakai, S., Nakaishi, H., Nakatsuka, M., Nishiguchi, A., Norreys, P.A., Setsuhara, Y., Takagi, M., Yamanaka M. & Yamanaka, C. (1991). High-density compression experiments at ILE, Osaka. *Laser Part. Beams* **9**, 167–208.

Badziak, J., Glowacz, S., Jablonski, S., Parys, P., Wolowski, J. & Hora, H. (2005). Laser-driven generation of high-current ion beams using skin-layer ponderomotive acceleration. *Laser Part. Beams* **23**, 401–409.

Badziak, J., Glowacz, S., Jablonski, S., Parys., P., Wolowski, J., Hora, H, Kraska, J., Laska, J. & Rohlena, R. (2004*b*). Production of ultrahigh ion current densities at Skin-Layer subrelativistic laser-plasma interaction, *Plasma Phys. Contr. Fusion* **46**, B541–B555.

Badziak, J., Glowacz, S.G., Jablonski, S., Parya, P., Wolowsk, J. & Hora, H. (2004*a*). Production of ultrahigh-current-density ion beams by short-pulse skin-layer laser-plasma interaction. *Appl. Phys. Lett.* **85**, 3041–3043.

Badziak, J., Hora, H., Woryna, S., Jablonski, S., Laska, L., Parys, P., Rohlena, K. & Wolowski, J. (2003). Experimental evidence of differences in properties of fast ion fluxes form short-pulse and long-pulse laser-plasma interaction. *Phys. Lett. A* **315**, 452–457.

Badziak, J., Kozlov, A.A., Makowski, J., Parys., P., Ryc, L., Wolowski, J., Woryna, E. & Vankov A. .B. (1999). Investigation of ion streams emitted from plasma produced with a high-power picosecond laser. *Laser Part. Beams* **17**, 323–329.

Balakirev, V.A., Kara, I.V., Karas, V.I., Levchenko, V.D. & Bornatici, M. (2004). Charged particle acceleration by an intense wake-field excited in plasmas by either laser pulse or relativistic electron bunch. *Laser Part. Beams* **22**, 383–392.

Bobin, J.L. (1971). Flame propagation and overdense heating in laser created plasma. *Phys. Fluids* **14**, 2341–2356.

Bobin, J.L. (1974). *Laser Interaction and Related Plasma Phenomena* (Schwarz, H. and Hora, H., Eds.). New York: Plenum.

Boody, F.P., Höpel, R., Hora, H. & Kelly, J.C. (1996). Laser-driven ion source for reduced-cost implantation of metal ions for strong reduction of dry friction and increased durability. *Laser Part. Beams* **14**, 443–448.

Brueckner, K.A. & Jorna, S. (1974). Laser driven fusion. *Rev. Mod. Phys.* **46**, 325–367.

Campbell, E.M. (1992). The physics of megajoule, large-scale, and ultrafast short-scale laser plasmas. *Phys. Fluids* **B4**, 3781–3799.

Campbell, E.M., Baldwin, D. & Blue, N. (2000). Congratulation message for Professor Chiyoe Yamanaka. In *Light and Shade: Festschrift to the 77th Birthday of Chiyoe Yamanaka*. Osaka University: ILE, pp. 470–472.

Campbell, E.M., Holmes, N.C., Libby, B.S., Remington, B.A. & Teller, E. (1997). The evolution of high-energy-density physics: From nuclear testing to the superlasers. *Laser Part. Beams* **15**, 607–618.

Cang, Y., Osman, F., Hora, H., Zhang, J., Badziak, J., Wolowski, J., Jungwirth, K., Rohlena, K., Ullschmied, J. (2005). Computations for nonlinear force driven plasma blocks by picosecond laser pulses for fusion. *J. Plasma Phys* **71**, 35–51.

Chu, M.S. (1972). Thermonuclear reaction waves at high densities. *Phys. Fluids* **15**, 413–422.

Clark, R., Hora, H., Ray, P.S. & Sir Ernest Titterton. (1978). Evaluation of cross sections of the $\mathrm{Li}(d,\alpha)\alpha$ reaction. *Phys. Rev. C* **18**, 1127–1132.

Clark, F.L., Krushelnik, K., Zepf, M., Beg, F.N., Tatarakis, M., Machacek, A., Santala, M.I.K., Watts, I., Norreys, P.A. & Dangor A.E. (2001). Energetic heavy ion and proton generation from ultraintense laser-plasma interactions with solids. *Phys. Rev. Lett.* **85**, 1654–1657.

Cockroft, J., *et al.* (1933). *Proc. Roy. Soc. London A* **137**, 229.

Deutsch, C. (2004). Penetration of intense charge particle beams in the outer layers of precompressed thermonuclear fuels. *Laser Part. Beams* **22**, 115–120.

Ehler, A.W. (1975). High-energy ions from a CO_2 laser-produced plasma. *J. Appl. Phys.* **46**, 2464–2467.

Eliezer, S. & Hora, H. (1989). Double layers in laser-produced plasmas. *Phys. Rep.* **172**, 339–406.

Esarey, E., Sprangle, P., Kroll, N.M. & Ting, A. (1997). Self-focusing and guiding of short laser pulses in ionizing gases and plasmas. *IEEE J. Quan. Electr.* **QE-33**, 1879–1891.

Esirkepov, T., Borghesi, M., Bulanov, S.V., Mourou, G. & Tajima, T. (2004). Highly efficient relativistic-ion generation in the laser-piston regime. *Phys. Rev. Lett.* **92**, 175003.

Gabor, D. (1953). Collective model for particle interaction in plasmas. *Proc. Royal Soc. London A* **213**, 73–92.

Gitomer, S.J., Jones, R.D., Begay, F., Ehler, A.W., Kephart, J.F. & Kristal, R. (1986). Fast ions and hot-electrons in the laser-plasma interaction. *Phys. Fluids* **29**, 2679–2688.

Greschik, F. & Kull, H.-J. (2004). Two-dimensional PIC simulation of atomic clusters in intense laser fields. *Laser Part. Beams* **22**, 137–147.

Hain, S. & Mulser, P. (2001). Fast ignition without hole boring. *Phys. Rev. Lett*., **86**, 1015–1018.

Hartemann, F.V. (2002). *Hugh Field Electrodynamics*. Baton Rough, FL: CRC Press.

Hartemann, F.V., Van Meter, J.R., Troha, A.L., Landahl, E.C., Luhmann, N.C., Baldis, H.A., Gupta, A. & Kerman, A.K. (1998). Three-dimensional relativistic electron scattering in an ultrahigh-intensity laser focus. *Phys. Rev. E* **58**, 5001–5012.

Haseroth, H. & Hora, H. (1996). Physical mechanisms leading to high currents of highly charged ions in laser-driven ion sources. *Laser Part. Beams* **14**, 393.

Häuser, T., Scheid. W. & Hora, H. (1994). Acceleration of electrons by intense laser pulses in vacuum. *Phys. Lett. A* **186**, 189.

Häuser, T., Scheid, W. & Hora, H. (1992). Theory of ions emitted in a plasma by relativistic self-focusing of laser beams. *Phys. Rev. A* **45**, 1278.

Hoffmann, D.H.H., Blazevic, A., Ni, P., Rosmej, O., Roth, M., Tahir, N.A., Tauschwitz, A., Udrea, S., Varentsov, D., Weyrich, K. & Maron, Y. (2005). Present and future perspectives for high energy density physics with intense heavy ion and laser beams. *Laser Part. Beams* **23**, 47–53.

Hora, H. (1969). Self-focusing of laser beams in a plasma by ponderomotive forces. *Zeitschrift d. Physik* **226**, 156–159.

Hora, H. (1973). Relativistic oscillation of charged particles in laser fields and pair production, *Nature (London) Phys. Soc.* **243**, 34.

Hora, H. (1975). Theory of relativistic self-focusing of laser radiation in plasmas. *J. Opt. Soc. Am.* **65**, 882–886.

Hora, H. (1983). Interpenetration burn for controlled inertial confinement fusion driven by nonlinear laser forces. *Atomkernenergie* **42**, 7–10.

Hora, H. (1985). The transient electrodynamic forces at laser-plasma Interaction. *Phys. Fluids* **28**, 3705–3706.

Hora, H. (1988). Particle acceleration by superposition of frequency-controlled laser pulses. *Nature* **333**, 337–338.

Hora, H. (1991). *Plasmas at High Temperature and Density*. Heidelberg: Springer.

Hora, H. (2000). *Laser Plasma Physics, Forces and the Nonlinearity Principle*. Bellingham WA: SPIE Press.

Hora, H. (2003). Skin-depth theory explaining anomalous picosecond-terawatt laser plasma interaction II. *Czech. J. Phys.* **53**, 199–217.

Hora, H. (2004). Developments in inertial fusion energy and beam fusion at magnetic confinement. *Laser Part. Beams* **22**, 439–449.

Hora, H. & Ray, P.S. (1978). Increased nuclear fusion yields of inertial confined dt plasma due to reheat. *Zeitschrift f. Naturforschung* **33A**, 890–894.

Hora, H. & Wang, L. (2001). Comments on measurements by J. Zhang *et al*., *Summit on Plasma Physics*, Feb., Islamabad.

Hora, H., Azechi, H., Kitagawa, Y., Mima, K., Murakami, M., Nakai, S., Nishihara, K., Takabe, K., Yamanaka, M. & Yamanaka, C. (1998). Measured laser fusion gains reproduced by self-similar volume compression and volume ignition for NIF conditions. *J. Plasma Phys.* **60**, 743–760.

Hora, H., Badziak, J., Boody, F., Höpfl, R., Jungwirth, K., Kralikowa, B., Kraska, J., Laska, L., Parys, P., Perina, V., Pfeifer, K. & Rohlena, J. (2002). Effects of ps and ns. laser pulses for giant ion source. *Opt. Commun.* **207**, 333–338.

Hora, H., Heolss, M., Scheid, W., Wang, J.X., Ho, Y.K., Osman, F. & Castillo R. (2000). Principle of high accuracy for the nonlinear theory of the acceleration of electrons in a vacuum by lasers at relativistic intensities. *Laser Part. Beams* **18**, 135–144.

Hora, H., Lalousis, P. & Eliezer, S. (1984). Analysis of the inverted double layers in nonlinear force produced cavitons at laser-plasma interaction. *Phys. Rev. Lett.* **53**, 1650–1652.

Hora, H., Miley, G.H. & Osman, F. (2005). Boltamann equilibrium o endothermic heavy nuclear synthesis in the universe and a quark relation to the magic numbers. *Astrophys. Space Sci.* **298** (in print).

Hora, H., Miley, G.H., Toups, P., Evans, P., Osman, F., Castillo, R., Mima, K., Murakami, M., Nakai, S., Nishihara, K., Yamanaka, C. & Yamanaka, T. (2003). Single event high compression inertial confinement of low temperature compared with the fast ignitor. *J. Plasma Phys.* **69**, 413–430.

Hora, H., Min, Gu, Eliezer, S., Lalousis, P., Pease, R.S. & Szichman, H. (1989). On surface tension in plasmas. *IEEE Trans. Plasma Sc.* **PS-17**, 284–289.

Hora, H., Osman, F., Castillo, R., Collins, M., Stait-Gardener, T., Wai-Kim, Chan, Hoelss, M., Scheid, W., Wang, Jia-Zhang & Ho, Yu-Kin (2002*a*). Laser-generated pair production and Hawking-Unruh radiation. *Laser Part. Beams* **20**, 79–78.

Hora, H., Osman, F., Höpfl, R., Badziak, J., Parys, P., Wolowski, J., Skala, J., Ullschmied, J., Wolowski, J., Woryna, E., Woryna, W., Boody, F., Jungwirth, K., Kralikowa, B., Kraska, J., Laska, L., Pfeifer, M., Rohlena, K., Skala, J. & Ullschmied J. (2002*b*). Skin depth theory explaining anomalous picosecond laser plasma interaction. *Czech. J. Phys.* **52**, D349–D361.

Jones, D.A. Kane, E.L., Lalousis, P, Wiles, P.R. & Hora, H. (1982). Density modification and energetic ion production at relativistic self-focusing of laser beams in plasmas. *Phys. Fluids* **25**, 2295–2302.

Joshi, C. & Katsoulease, T. (2003). Plasma accelerators at the energy frontier and on tabletops. *Physics Today* **56**, 47.

Katsouleas, T. (2004). Progress on plasma accelerators: from the energy frontier to tabletops. *Plasma Phys. Contr. Fusion* **46**, B575.

Key, H.M. (2001). Fast track to fusion energy. *Nature* **412**, 775–776.

Kitagawa, Y., Matsumoto, T., Minamihata, T., Sawai, K., Matsuo, K., Mima, K., Nishihara, K., Azechi, H., Tanaka, K.A., Takabe, H. & Nakai, S. (1992). Beat-wave excitation of plasma-wave and observation of accelerated electrons. *Phys. Rev. Letters* **68**, 48–51.

Kodama & Fast Ignitor Consortium (2002). Fast heating scalable to laser fusion ignition. *Nature* **418**, 933–943.

Kruer, W.L. (1988). *Physics of Laser Plasma Interactions*. Redwood City, CA: Addison-Wesley.

Ledingham, K.W.D., Spencer, I., Mccanny, T., Singhal, R.P., Santala, M.I.K., Clark, E., Watts, I., Beg, F.N., Zepf, M., Krushelnik, K., Tatarakis, M., Dangor, A.E., Norreys, P.A., Allott, R., Neely, D., Clark, R.J., Machacek, A.C., Wark, J.S., Cresswell, A.J., Sanderson, D.C.W. & Magill, J. (2000). Photonuclear physics when a multiterawatt laser pulse interacts with solid targets. *Phys. Rev. Lett.* **84**, 899–902.

Leemans, W.P., Rodgers, D., Catravas, P.E., Geddes, C.G.R., Fubiani, G., Esarey, E., Shadwick, B.A., Donahue, R. & Smith, A. (2001). Gamma-neutron activation experiments using laser wakefield accelerators. *Phys. Plasmas* **8**, 2510–2516.

Lefebvre, E., Malka, G. & Miquel, J.L. (1998). *Phys. Rev. Lett.* **80**, 1352.

Leon, P.T., Eliezer, S., Martinez-Val, S. & Piera, M. (2001). Fusion burning waves in degenerate plasmas. *Phys. Lett.* **A289**, 135.

Li, X.Z., Tian, J., Mei, M.Y. & Li, C.X. (2000). *Phys. Rev.* **C61**, 0246101.

Li, X.Z., Liu, B., Chen, S.I., Wei, Q.M. & Hora, H. (2004). Fusion cross-sections for inertial fusion energy. *Laser Part. Beams* **22**, 469.

Limpouch, J., Klimo, O., Bina, V. & Kawata, S. (2004). Numerical studies on the ultrashort pulse K-α emission sources based on femtosecond laser-target interactions. *Laser Part. Beams* **22**, 147–156.

Magill, I., Schwoerer, H., Ewald, F., Galy, F., Schenkel, R. & Sauerbrey, R. (2003). Terawatt laser pulses for transmutation of long lived nuclear waste. *Appl. Phys.* **B77**, 387–392.

Malka, V. & Fritzler, S. (2004). Electron and proton beams produced by ultra short laser pulses in the relativistic regime. *Laser Part. Beams* **22**, 399.

Miley, G.H., Hora, H., Osman, F., Evans, P. & Toups, P. (2005). Single event laser fusion using ns-MJ laser pulses. *Laser Part. Beams* **23**, 453–460.

Miley, G.H. *et al.* (2004). *SPIE Proc.* **5448**, 973.

Miley, G.H., *et al.* (2003). *Inertial Fusion Science and Application* (Hammel, B.A., *et al*., Eds.), p. 418. LaGrange, IL: American Nuclear Society.

Mourou, G. & Tajima, T. (2002). Ultraintense lasers and their applications. In *Inertial Fusion Science and Applications 2001* (Tanaka, K.A., Meyerhofer, D.D. and Meyer-ter-Vehn, J., Eds.), p. 831–839. Paris: Elsevier.

Mulser, P. & Bauer, D. (2004). Fast ignition of fusion pellets with superintense lasers: Concepts, problems and prospectives. *Laser Part. Beams* **22**, 5–12.

Mulser, P. & Schneider, R. (2004). On the inefficiency of hole boring in fast ignition. *Laser Part. Beams* **22**, 157.

Nuckolls, J.L. & Wood, L. (2002). *Future of Inertial Fusion Energy*. Livermore, CA: Lawrence Livermore National Laboratory. Preprint, UCRL-JC-149860.

Oliphant, M.L.E., Harteck, P. & Lord Rutherford. (1934). Transmutation effects observed with heavy hydrogen. *Proc. Roy. Soc. London A* **144**, 692–714.

Osman, F., Ghahramann, N. & Hora, H. (2005). Debye sheath mechanism at laser plasma interaction and generalization to nuclear forces and quark-glucon plasma. *Laser Part. Beams* **23**, 461–466.

Osman, F., Beech, R. & Hora, H. (2004*a*). Solutions of the nonlinear paraxial equation due to laser-plasma interactions. *Laser Part. Beams* **22**, 69–74.

Osman, F., Castillo, R. & Hora, H. (1999). Relativistic and ponderomotive self-focusing at laser-plasma interaction. *J. Plasma Phys.* **61**, 263–273.

Osman, F., Hora, H., Cang, Y., Evans, P., Cao, L.H., Liu, H., He, X.T., Badziak, J., Parys, A.B., Wolowski, E., Woryna, E., Jungwirth, K., Kralikova, B., Krasla, J., Laska, J., Pfeifer, M., Rohlena, K., Skala, J. & Ullschmied, J. (2004*b*). Skin depth plasma front interaction mechanism with prepulse suppression to avoid relativistic self focusing for high gain laser fusion. *Laser Part. Beams* **22**, 83–88.

Perry, M.V. & Mourou, G. (1994). Terawatt to petawatt subpicosecond lasers. *Science* **264**, 917–924.

Roth, M., Cowan, T.E., Hunt, A.W., Johnson, J., Broen, S.P., Fountain, W., Hatchett, S.P., Henry, E.A., Key, M.H., Kuehl, T., Parnell, T., Pennington, D.W., Perry, M.D., Sangster, T.C., Christi, M., Singh, M., Snavely, R., Stoyer, M., Takahashi, Y. & Wilks, S.C. (2000). High-energy electron, positron, ion and nuclear spectroscopy in ultra-intense laser-solid experiments on the petawatt. In *Inertial Fusion Science and Applications 1999* (Labaune, C., Hogan, W.J. & Tanaka, K.A., Eds.), pp. 1010–1015. Paris: Elsevier.

Roth, M., Cowan, T.E., Key, M.H., Hatchett, S.P., Brown, C., Fountain, W., Johnson, J., Pennington, D.W., Snavely, R.A., Wilks, S.C., Yasuike, K., Ruhl, H., Pegoraro, F., Bulanov, S.V., Campbell, E.M., Perry, M. .D. & Powell, H. (2001). Fast ignition by intense laser accelerated proton beams. *Phys. Rev. Lett.* **86**, 436–43.

Sari, A.H., Osman, F., Ghoranneviss, M., Hora, H., Hopel, R., Benstetter, G. & Hantehzadeh, M.H. (2005). Application of laser driven fast high density plasma blocks for ion implantation. *Laser Part. Beams* **23**, 467–473.

Sauerbrey, R. (1996). Acceleration in femtosecond laser produced plasmas. *Phys. Plasma* **3**, 4712–4716.

Schäfer, F.P. (1986). *Appl. Phys.* **B39**, 1.

Schaumann, G., Schollmeier, M.S., Rodriguez-Prieto, G., Blazevic, A., Brambrink, E., Geissel, M., Korostity, S., Pirzadehi, P., Roth, M., Rosmej, F.B., Faenov, A.Ya., Pikuz, T.A., Tsigutkin, K., Maron, Y. & Tarhir, N.A. (2005). High energy heavy ion jets emerging from laser plasma generated by long pulse laser beams from NHELIX laser system at GSI. *Laser Part. Beams* **23**, 503–511.

Scheid, W. & Hora, H. (1989). On Electron acceleration by plane transverse electromagnetic pulses in vacuum. *Laser Part. Beams* **7**, 315–332.

Schwoerer, H., Gibbon, P., Duesterer, S., Behrens, K., Ziener, C., Reich, C. & Sauerbrey, R. (2001). *Phys. Rev. Lett.* **86**, 2317–2320.

Shorokhov, O. & Pukhov, A. (2004). Ion acceleration in overdense plasma by short laser pulse. *Laser Part. Beams* **22**, 175.

Tabak, M., Glinsky, M.N., Kruer, W.L., Wilks, S.C., Woodworth, J., Campbell, E.M., Perry, M.D. & Mason, R.J. (1994). Ignition and high-gain with ultrapowerful lasers. *Phys. Plasmas* **1**, 1626–1634.

Teubner, U., Bergmann, B., Van Wontergehm, B., Schäfer, F.P. & Sauerbrey, R. (1993). Angle dependent X-ray emission and resonance-absorption in a laser produced plasma generated by a high-intensity ultrashort pulse. *Phys. Rev. Lett.* **70**, 794–797.

Thomas, O. (2004). Planning of the acceleration after LHC. *Phys. J.* **3**, 14–15.

Umstadter, R. (1996). Terawatt lasers produce faster electron acceleration. *Laser Focus* **32**, 101–107.

Wägli, P. & Donaldson, Z. (1978). *Phys. Rev. Lett.* **40**, 875–878.

Wang, J.X., Ho, Y.K., Kong, Q., Zhu, L.J., Feng, J., Scheid, W. & Hora, H. (1998). Electron capture and violent acceleration by an extra-intense laser beam. *Phys. Rev. E*, **58**, 6576–6577

Wilks, S.C., Kruer, W.L., Tabak, M. & Langdon, A.B. (1992). Absorption of ultra-intense laser pulses. *Phys. Rev. Lett.* **69**, 1383–1386.

Wilks, S.C., Langdon, A.B., Cowan, T.E., Roth, M., Singh, M., Hackett, S., Key, M.H., Pennington, D., Mckinnon, A. & Snavely, R.A. (2001). *Phys. Plasmas* **8**, 542.

Wolowski, J. Badziak, F., Boody, B., Hora, H., Hnatowicz, V., Jungwirth, K., Kraska, J., Laska, L., Parys, P., Perina, V., Pfeifer, M., Rohlena, K., Ryc, L., Ullschmied, J. & Woryna, E. (2002). Fast ion emission from the plasma produced by the PALS laser system. *Plasma Phy. Contr. Fusion* **44**, 1277–1283.

Wolowski, J., Badziak, J., Boody, B., Gammino, S., Hora, H., Jungwirth, K., Kaska, J., Laska, L., Parys, P., Pfeifer, M., Rohlena, K., Szydlowski, A., Torris, L., Ullschmied, J. & Woryna, E. (2003). Characteristics of ion emission from plasma produced by high-energy short-wavelength (438 nm) laser radiation. *Plasma Phys.Contr. Fusion* **45**, 1087–1099.

Woryna, E., Wolowski, J., Kralikowa, B., Kraska, J., Laska, L., Pfeifer, M., Rohlena, K., Skala, J., Perina, V., Booday, F.P. & Hora, H. (2000). Laser produced ag ions for direct implantation. *Rev. Sci. Instr.* **71**, 949–951.

Zhang, P., He, J.T., Chen, D.B., Li, Z.H., Zhang, Y., Wong, Lang, Li, Z.L., Feng, B.H., Zhang, D.X., Tang, X.W. & Zhang, J. (1998). X-Ray emission from ultraintense-ultrashort laser irradiation. *Phys. Rev.* **E57**, 3746–3752.