TW-ps laser driven blocks for light ion beam fusion in solid density DT

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ABSTRACT

It is being clarified why the observations of plane wave geometry *interaction within the skin depth* of a laser irradiated target are very unique exceptions from the broad stream of the usual experiments of laser plasma interaction. This permits a much more simplified description by plane wave interaction theory for laser pulses of about ps or shorter duration and powers above TW and simplifies computations in contrast to the usual cases with relativistic self-focusing. After establishing theoretically and experimentally the generation of highly directed *plasma blocks with ion current densities above* 10^{10} *A/cm*^{2} moving against the laser light or into the target, applications for laser fusion, and a completely new improvement of ion sources for the next generation of accelerators are discussed.

Key words: Laser produced plasmas, Relativistic self-focusing, Nonlinear (ponderomotive) force, Controlled thermonuclear fusion energy, Laser fusion,

1. INTRODUCTION

It is a rare opportunity how very marginal and very little noted experimental and theoretical developments within the broad stream of the established research may contribute to result in a chance for solving the energy production by nuclear fusion in some alternative ways by application of lasers. The key element for this development is the chirped pulse amplification (CPA) pioneered by Gerard Mourou [1] of laser pulses reaching today more than PW (10^{15}W) power with pulses of ps or shorter duration. Another technique uses excimer lasers pioneered by Fritz-Peter Schäfer [2]. The other ingredients are the unique measurements with TW-ps laser pulses beginning with the observation of Doppler shifts from irradiated targets by Roland Sauerbrey [3], the anomalies of x-ray emission from targets clarified by most precise studies of the influence of prepulses by Jie Zhang et al [4] and the very transparent measurements of ion generation in comparison with longer pulses by Jan Badziak et al [5].

The uniqueness of these observations consists in the discovery of the fundamental difference to all the broad stream observations leading to relativistic self-focusing dominates the interaction, where MeV to GeV highly ionised ions are generated with intense electron beams of 100 MeV and higher energy, electron positron pairs while 10 MeV gammas produce unusual nuclear reactions. In contrast to this, the suppression of relativistic self-focusing in the unique experiments permitted a comeback to the transparent and simplified theory of plane wave interaction of the laser pulse as a skin layer process [6]. A consequence is indeed that these unique conditions may lead to a new scheme for laser fusion. The basically new aspects for ion sources for feeding accelerators may provide a one new ingredient for planning the design of the next generation of accelerators after the large hadron collider (LHC) [7].

The struggle with the usual broad stream observations is well known where the discovery of nonlinear effects, of relativistic phenomena and even of a quantum mechanical component to the otherwise classical plasma phenomena was dominating [8,9] apart from several misleading considerations of resonance absorption and overe-

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High-Power Lasers and Applications III, edited by DianYan Fan, Keith A. Truesdall Koji Yasui,
Proceedings of SPIE Vol. 5627 (2004) p. 51-63

stimation of parametric instabilities which processes could mostly be excluded experimentally by laser beam smoothing and where some explanations were given from the observation of 10-ps stochastic pulsation processes. To summarize these usual interaction processes, a short review of the long years developments is given in Section 2.

The unique different observations are then summarized in Section 3. In order to illustrate the conditions of the application to laser fusion, Section 4 summarizes some aspects into this direction before Section 5 presents some results and explains problems how the unique results of the discovery of interaction without relativistic self-focusing may lead to an alternative scheme of laser fusion.

2. HISTORICAL SUMMARY ON LASER DRIVEN ION EMISSION

The measurement of ion energies and high current densities from laser irradiated targets in vacuum was the first experience of the very unexpected and extreme anomalies in this new field of laser-plasma interaction physics after the clean Q-switch laser pulses were available in 1962. If laser powers of less than about 1 MW was incident, all was classical [10], the generated plasmas behaved fully thermodynamically with ion energies between 2 and 5 eV according to the generated temperatures of few ten thousand degrees. The electrical current densities of the emitted ions were about 100 mA/cm^2 as known form the classical Child-Langmuir space charge limitation which dominates all emission processes including the most advanced MEVVA or ECR sources [6]. In contrast to this, as soon as the laser power P exceeded a threshold P*

$$P > P^* = 1\ \text{MW} \tag{1}$$

the electron emission current density was more than ten thousand times higher [12] and the energy of the ions was not few eV but few keV [13].

This was the starting point for the studies of the anomalous processes of laser-plasma interaction [14]. It led finally to the measurement of MeV ions [15,16] where the discovery of Ehler [15] has to be underlined that there were three groups of ions the fastest group the second fastest group and the unavoidably remaining thermal plasma. A clear reproduction of the three groups from irradiated silver can be seen in Fig. 2a of [17]. The second group was reported explicitly in the summary of Gitomer [18] where the special property of this type of fast ions found special attention [19] (Chap. 5) with respect to a proof of the a quantum modification of the collision frequency [20].

2.1 THE FASTEST ION GROUP

The highly charged ions of 10 keV and higher energy from laser produced plasmas with laser pulses of higher power than 1 MW were separated in groups with linear increase of the ion energy on the charge number Z. The measured number of 10^{13} and many more ions is too large than an explanation can be given by an ambipolar acceleration from the Debye surface sheath which could account only to about 10^9 ions at the most. When looking into other acceleration mechanisms, self-focusing was an explanation [21] based on th the first derived dielectric modification of the ponderomotive force generalized to the nonlinear force [8,9,22], Three conditions had to combined:(a) the fact that the radial nonlinear force $-\nabla\mathbf{E}^2$ with the averaged electric laser field **E** acting on the plasma radial in the laser beam will be compensated by gas dynamic -p of the pressure p due to depletion of plasma from the beam center, (b) the dielectric bending and total reflection of the plasma beamlets in the filament, and (c) the diffraction conditions of the beam. The result is that self-focusing appears above a laser power P of about 1 MW. This process including the beam diameter and the measurements of the plasma depletion in the beam axis was measured in all details in agreement [23] with the theory derived later by a number of authors in a different way and all resulting in the same numbers [8](Chap. 12.1).

This showed how the MW threshold ofr Eq. (1) led to a laser intensity in the filament such that that the nonlinear force accelerated the whole volume of the electron cloud with the attached ions, but separated by Z, to the 10 keV energies. This process to the electron cloud with the strong gradient of the electromagnetic laser field energy [22] including the dielectric properties was like a gravitation but with differentiating according to Z.

Apart from this plasma dynamics driven by the laser field above 1 MW, another *instantaneous* self-focusing appeared purely dielectric when the quiver energy of the electrons in the laser field were at least about one thousandth of the relativistic electron energy mc^2 [20]. The laser beam was shrinking down to a diameter of multiples δ of the laser wave length λ. The extremely high laser intensities in the filament resulted than in a nonlinear force acceleration to the MeV energies. This agreed with all the highest ion energies measured all different times at different laboratories [19] (Fig. 10) before the ps laser pulses were available. The maximum ion energy ε_{ion} is then independent of the wave length λ and is determined only by the laser power P in watts as [24.25]

$$\varepsilon_{trans} = Z\, mc^2 Pe^2/(\pi^2\delta^2 m^2 c^5) = Z\, mc^2\, (P/\delta^2)\, 5.7 \times 10^{-12}\ \mathrm{W} \qquad (2)$$

where δ is a self diffraction factor given in multiples of the wave length which may vary around one wave length (δ=1) though there were experimental indications that this can be as low as 0.6 [8]. Since we have to compare ion energies differing by orders of magnitude in the following, we do not need to go into the finer accuracy and error bars of the experiments.

One example from recent experiments with the PALS iodine laser [26] are the following. A third harmonics iodine laser pulse of 0.4 ns duration and 6×10^{11} W power irradiating tantalum produced fastest 81 MeV Ta^{+50} ions. The theory of relativistic self-focusing, Eq. (2) with $\delta = 1$ arrives at 89 MeV. This is a rather sufficient confirmation that the vary fast ions were produced by relativistic self focusing and subsequent nonlinear force acceleration.

2.2 THE SECOND FASTEST ION GROUP

For the second fastest ion group it was explained before from the observed properties [19] that this may be due to the *partial thermalization* of the high electron quiver energy where a subsequent acceleration process of these hot plasma electrons will occur. After this thermalization, the ions gain energy by ambipolar acceleration, however, to much higher energies and ion numbers than from the thermal plasma. The ion numbers are still less than that of the fastest ion group due to relativistic self-focusing (see preceding Subsection). In this view, the long known phenomenon of the "hot electrons" discovered from x-ray emission by Eidmann (see [8,14]) led to the consideration of a thermokinetic description [6,19] where the nonlinear phenomenon involved is the quiver motion of the electron in the laser field.

The detailed study of this group of ion emission as a "quiver-thermalization" process is of special interest because this leads to another proof of the *quantum modification* of the plasma collisions as it was successfull initially to reproduce the measured hot-electron caused x-ray emission, see Chapter 5 of Ref. [19]. This question is important also for understanding of the mechanisms at magnetic confienement fusion, see chapter 2.6 of Ref. [8]. The degree of thermalization of the energy of the quivering electrons was studied depending on the collision frequency. We used the quantum modified collision frequency [20]

$$\nu = \begin{cases} \nu_c \\ \nu_c\, T/T^* \end{cases} \qquad (3)$$

where nc is the classical electron-ion collision frequency, T is the plasma temperature and

$$T^* = 4Z^2 mc^2\alpha/3k = Z^2\, 36.9\ \mathrm{eV} \qquad (4)$$

The use of this result for explaining the measured diffusion in stellarators or the thermal conduction in tokamaks has been show before [8,9,20].

The hot temperature T_x measured also by the high energy x-ray emission in the plasmas at laser radiation during a laser pulse length τ_L is then given in the range of quantum domination [19] by

$$T_x = \mathrm{const}\ \tau_L\, I^{1/2} \qquad (5)$$

while the use of the classical collision frequency arrives at

$$T_x \propto I^{-1/2} \qquad (6)$$

The evaluation of the numerous results compiled by Gitomer et al [18] indicated that the measured x-ray temperature followed the relation (5) with the positive exponent 1/2 and not with the negative exponent of the classical dependence on the laser intensity I.

This result can now be extended to the ps laser plasma interaction experiments by Clark et al [28]. 50 TW 0.9-

2.3 ps neodymium glass laser pulses were focused to 10 wave length beam diameter at an obliquely arranged target where strong suppression of any prepulse produced a plasma in front of the target of less then 10 wave length thickness. The highest energies of Pb^{+48} was 430 MeV while the fastest C^{+6} ions had 60 MeV energy. The fact that the lead ions should have 7.1 GeV and the carbon ions about 880 MeV energy if relativistic self-focusing had been involved (Eq. (2)), indicates that the ions were rather not due to relativistic self-focusing. The conditions of the 10 wave length focus and the thin pre-plasma may indicate qualitatively that relativistic self-focusing could not have been established but that the *quantum modified quiver-thermalization* process (hot electron acceleration) is driving the ions.

It is very important to note that the measurement of the intensity dependence (Fig. 4 of Ref. [28]) at the unchanged wavelength showed an increase of the maximum ion energy ε_{imax} of the fastest ions is close to

$$\varepsilon_{imax} \propto I^{1/2} \tag{7}$$

This is in rather good agreement with Eq. (5) since the pulse duration was constant. This may be a confirmation that the measured fast ions were only due to the quiver-collision-thermalization process as known from the usual second fastest ion group because the relativistic self-focusing relation, Eq. (2) would have had an exponent 1 and not 0.5 as measured [28]. Obviously there was not at all the fastest ion group from relativistic self-focusing but only from the quiver-collision mechanism as known from the usual second fastest ion group.

2.3 OTHER USUAL OBSERVATIONS

The complexity of the laser plasma interaction as observed in all the large number of usual cases in the past can not immediately classified as it was possible with the MeV ion generation. The fact that neither resonance absorption nor the long assumed parametric instabilities are dominating, could be seen when the laser beam smoothing [29] was introduced. This smoothing was reducing the generation of 3/2 harmonics and other parameters which were assumed to be related to the instabilities by more than a factor 100 [30]. On the other hand, smoothing was increasing direct drive fusion gains by more than a factor 10 [31]. It was revealed that the complexity of the interaction was mainly due to a 10 to 30 ps stochastic pulsation of the interaction as measured directly [32] and that this was due to nonlinear force produced density ripples by the partial standing waves and their thermal relaxation such that the broad band smoothing of the random phase plate smoothing immediately could lead to the suppression of the phase reflection from the ripples as clearly reproduced numerically [33].

The phenomena at the use of ps and short pulses at laser powers above TW lead to another order of complications where, however, relativistic self-focusing was well of importance. The generation of 30 MeV electrons of large numbers (10^8) per irradiation with 30 TW ps laser pulses [34] could immediately explained by a free wave electron acceleration including relativisitic self focusing [35]. Observations of ions of half GeV energy were just mentioned [28] while the generation of very intense proton beams of 5 MeV [36] may be used for spark ignition in laser compressed deuterium-tritium (DT). For the first time, large numbers of positrons were generated [37], the generation of very intense short pulses of gamma radiation led to nuclear photo-effect and radioactive isotopes [38] including reaction for the elimination of long lived nuclear waste [39]. The involvement of relativistic self-focusing in most of these cases did not simplify the theoretical clarification of these processes while in the experiments of fast ignition for laser fusion, the involvement of relativistic self-focusing was an essential ingredient [40].

3. DISCOVERY OF THE UNIQUE INTERACTION WITHOUT RELATIVISTIC SELF-FOCUSSING

In view of the partially clarified and the unclarified phenomena just mentioned, the following discussion is about few cases out of the usual main stream of the laser plasma interaction research which cases were rare and differ significantly and may be categorized as *unique*. They may even be described as being based on much more simplified conditions of plane geometry mostly due to the fact that *relativistic self-focusing could be excluded* leading to a more transparent modeling despite all the numerous confusing aspects which are known form the usual research. This is the reason why we are underlining these differences and extended the consideration of Section 2 since the unique experiments needed a lot of understanding from the viewpoint of the usual main stream of research.

The key question is whether there are conditions that the interaction of a focussed laser beam at the surface of a solid target in vacuum is following the conditions of a plane wave interaction described preferably one dimension, or whether the laser beam – as in most of the usual cases enters - a pre-generated plasma in front of the target, performs self -focusing and undergoes a very complicated shrinking to wavelength diameter beamlets as described in Section 2.1 with subsequent enormous nonlinear forces for producing MeV to GeV ions and strong x-ray emission. The plane wave interaction was studied by hydrodynamic codes including nearly all realistic and general plasma properties [8,14](see Chap. 10.3) of which one of the numerous cases is shown in Fig. 1. Within two ps interaction of a 10^{18} W/cm^2 pulse on a deuterium target with an initially very low reflection (bi-Rayleigh) density profile, the nonlinear force is generating blocks of plasma of several vacuum wave lengths thickness with velocities exceeding 10^9 cm/s moving against the laser light and a similar block moving into the target interior.

It was many years later that such velocities gained by irradiation of similar excimer laser intensities at less than a ps duration did produce such velocities as measured in all details from the Doppler shift by Sauerbrey [3]. The resulting accelerations were in full agreement with the expectation from the nonlinear force interaction. Another key experiment was that by Zhang et al [4] where 100 fs TW laser pulses were focused to about 30 wave lengths diameter onto a target and the x-ray emission was measured. The laser pulses produced very much lower x-rays than known from other experiments with the same intensities. The uniqueness of the experiment [4] consists in the procedure, that a lower intensity similar pulse was irradiated on the target at varying times between 10 to 100ps *before* the main pulse. At short time pre-irradiation, no change of the low x-ray emission was seen, but as soon as the pre-pulse time reached 70 ps and more, suddenly the very high x-ray emission appeared as known from all the usual main stream experiments. The later given explanation was evident: thanks to the clean laser pulse technique [4] where the contrast ratio for the main pulse was 10^8 (ratio of suppression of any pre-pulse). When the 70 ps prepulse was incident, a plasma plum was generated of a depth about two times the focus diameter. This was sufficient that the main pulse was shrinking to about one wave length diameter by relativisitc self-focusing such that the then very high x-ray intensities resulted as in the usual cases.

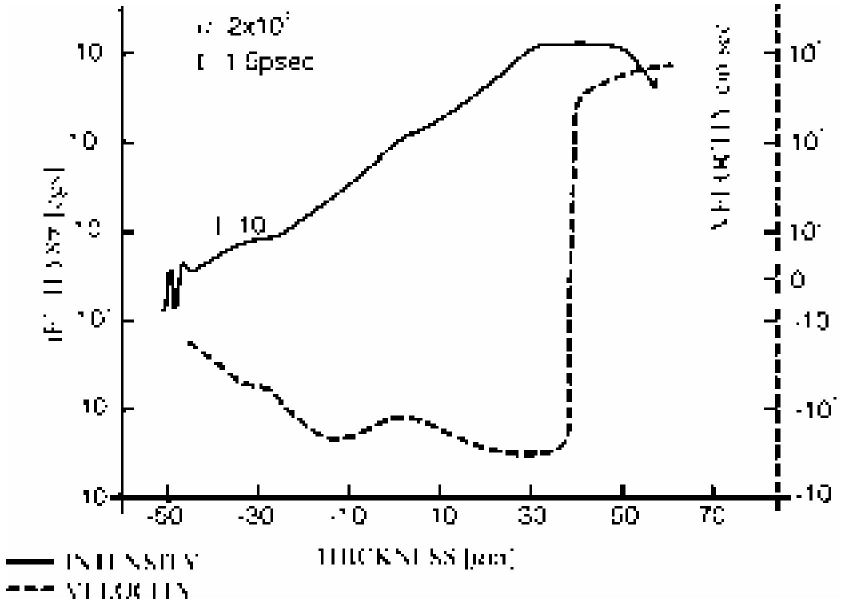

Fig. 1 Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100 eV hot and 100 μm thick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

These both experiments [3,4] were a clear confirmation of the plane wave plasma interaction, in agreement with the plane wave interaction theory, Fig. 1, and the exclusion of the self-focusing theory [8,24,25] would not have been very intriguing. The drastic problems appeared with the experiments by Badziak et al [5] from the studies of ion emission with high contrast ratio ps-TW laser pulses. This mutually confirmed the high contrast ratio of the excimer laser pulses [3] as well as the very clean techniques of the other experiments [4,5]. The experiments [5] with copper target should have led to Cu^{+13} ion of 22 MeV due to relativistic self focusing, but only 0.5 MeV ions were detected. Furthermore it was strange that the *number of the fast ions did not change* at all when the laser intensity was varying by a factor 30 while the energy of the fast ions was fully linear on the laser intensity (excluding the hot electron mechanisms of Section 2.2) as expected from a nonlinear force acceleration. The measured x-ray emission leading to a quiver energy swelled dielectrically by a factor three fully satisfactorily explained the measured ion energies from a plane wave interaction which was taking place within the skin depth of intensity of independent volume. This confirmed the observation of the intensity independence of the fast ions. These experiments were repeated with gold targets confirming all the details of the skin layer mechanism [11] including the generation of the plasma block moving into the target as experimentally confirmed from thin irradiated films [41] and confirming an ion current density in the blocks above

$$j > 10^{10} \text{ A/cm}^2. \tag{8}$$

The measurements confirmed also [11] that the ps-TW interaction resulted only in one narrow ion beam accelerated against the laser light as expected from the nonlinear force acceleration while the use of longer laser pulses as usually resulted in several groups of ions moving into a wide angle against the laser light [25] (see Fig. 4 of Ref. [11]). We report here about some details including recent numerical results [42,43]. It should be mentioned from experiments with sub-picosecond pulses above 5 TW power how plasma block generation can directly be recognized from the resulting ion and x-ray emission such that the sufficiently contrast ratio could concluded indirectly [44] such that the usual vague speculations about resonance absorption or parametric effects could be ignored.

The following computations are based on the fact that before the ps main pulse, a less than 50 ps earlier acting laser prepulse produces a preplasma layer of the thickness L_{pre} at least several times smaller than the laser focal spot diameter d_f. The main laser pulse interacts most intensively with the plasma in the skin layer near the surface of the critical electron density $n_{ec} = m_e\omega^2/4\pi e^2$ (ω is the laser frequency) and the geometry of the interaction is almost planar ($L_{pre} << d_f$). The high plasma density gradient in the interaction region produces non-linear ponderomotive forces acting – at the laser beam incidence perpendicular to the target surface – nearly parallel to the target normal. The force density f_{NL} can be expressed approximately as one-dimensional negative gradient of the electromagnetic energy density of the laser field given by its (dielectric modified) electric and magnetic vectors $\mathbf{E}$ and $\mathbf{H}$ [6]: $f_{NL} = -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/8\pi$. The gradients of the energy density near the critical surface result in two opposite non-linear forces which break the plasma and drive two thin ($\sim \lambda$) plasma blocks towards vacuum and towards the plasma interior, respectively (λ is the laser wavelength). The density of the plasma blocks is high (the ion density $n_i \approx n_{ec}/z$, where z is the ion charge state) but the electron temperature is fairly moderate at subrelativistic laser intensities. Thus, the Debye length, λ_D, is small ($\lambda_D << \lambda$) inside the block and ions – being closely attached to electrons – move together with the electron cloud driven directly by the ponderomotive force. Since $n_i \sim 10^{21} - 10^{22}\text{cm}^{-3}$ at $\lambda \sim 0.3 - 1\mu\text{m}$, even at moderate ion velocities $v_i \sim 10^7 - 10^8$ cm/s, the ion current densities can be very high ($\sim 10^9 - 10^{10}$ A/cm^2 or higher).

The computation use the genuine two-flud model [8,43] and are performed for a 20-μm hydrogen, inhomogeneous plasma layer of initial density increasing in the direction of the laser beam propagation. Both the linear plasma density profile and the profile described by the function $n_e(x) = 2xn_{ec}\{1+\exp[(x-x_c)/05.L_n]\}^{-1}$ were considered as initial values. For both profiles the boundary plasma densities were chosen in such a way that the critical plasma density n_{ec} was placed near the middle of the layer. The initial inhomogeneity of the plasma was characterised by the (relative) plasma density gradient scale length, L_n/λ, where $L_n = n_{ec}(\partial n_e/\partial x)^{-1}{}_{x=}$. The initial temperatures of both electrons and ions were assumed to be of 30eV. Most of the calculations were carried out for laser pulses of a Gaussian shape and for a laser wave length $\lambda = 1.05$ μm. Our numerical studies were focused on the influence of the initial plasma inhomogeneity and the laser pulse parameters (intensity, duration) on the plasma characteristics and, particularly, on the current densities and velocities of ion fluxes produced by the laser-plasma interaction. The following results are for the non-linear initial plasma density profile and the results for the linear profile were qualitatively similarFig. 2 presents spatial distributions of the ion velocity, the ion current density, the ion density and the electron temperature of plasma for the three time intervals after the beginning of the laser-plasma interaction. We see the generation of the underdense plasma block moving against the laser (negative velocities and current densities) and the overdense plasma block behind the critical surface moving in forward laser direction (positive velocities and current densities) in accordance with the simple physical picture described in the chapter 2. The plasma density profile is significantly disturbed near the critical surface and the electron temperature is the highest there.

Fig.2

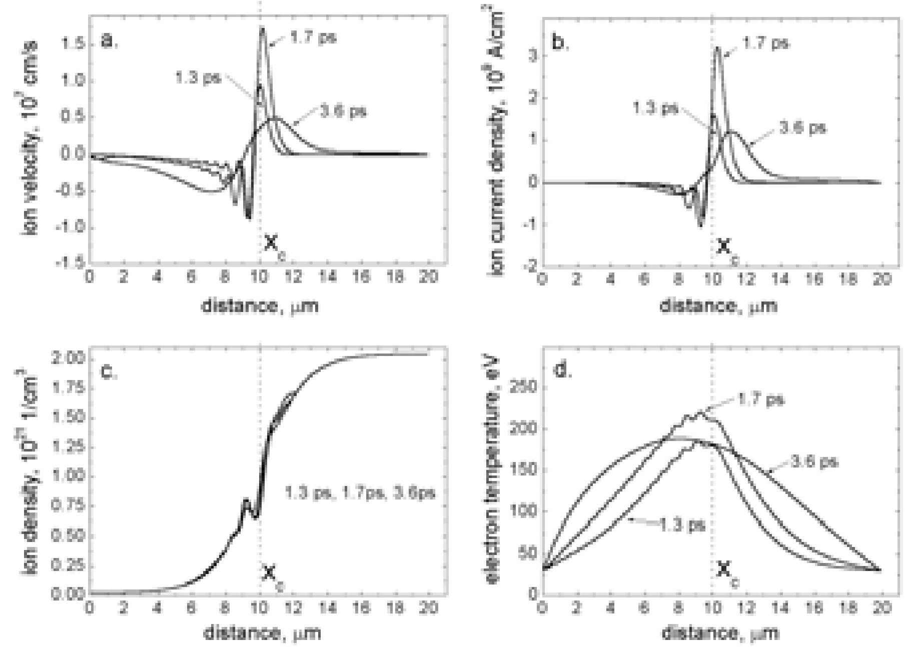

Fig. 2. Spatial distributions of the ion velocity (a), the ion current density (b), the ion density (c) and the electron temperature (d) of plasma for various times measured from the beginning of the laser-plasma interaction. $\tau_L = 1$ *ps ,* $I_L = 10^{16}$*W/cm*^{2} *,* $L_n/\lambda = 2.5$*.*

The effect of the plasma density gradient scale length on the maximum ion current densities and the maximum ion velocities of backward- and forward-emitted ion fluxes can be seen in Fig. 3. For both fluxes there exist optimum values of L_n/λ but they are located in essentially different regions of L_n/λ: the highest current densities and velocities for the backward flux are attained at the small density gradients and for the forward flux – at the high density gradients.

The dependencies of the maximum ion current densities and the maximum ion velocities on the 1-ps laser pulse intensity, I_L – plotted in the form of power functions – are presented in Fig. 4. In the case of backward-emitted ions, both the current density and the velocity follow approximately the square-root dependence on I_L in agreement with a simplified theory and measurements [41,45]. However, for the forward flux these quantities increase faster with an increase in I_L and nearly linear dependence of the velocity on I_L is observed.

The influence of a laser pulse duration, τ_L, on characteristics of ion fluxes is illustrated in Fig. 5. For the forward-emitted ions, the maximum ion velocity and the maximum ion current density continuously increase with an elongation of the laser pulse. Contrary to that, in the case of backward-emitted ions distinct maxima of these quantities occur at τ_L from the subpicosecond range.

One of the characteristic features of the dependencies presented in Fig. 3, 4 and 5 are essential differences in the run of these dependencies for forward- and backward-emitted ion fluxes. These differences can be understood better when we consider the dielectric swelling factor $S=1/|n|$ which is a measure of increase in the electromagnetic energy density of the laser field in plasma in relation to its vacuum value (n is the plasma refractive index) [6]. The necessary condition for the acceleration of plasma (ions) by the ponderomotive force in the backward direction is $S > 1$ and, usually, the higher S, the higher backward-directed ponderomotive force. The swelling factor depends not only on the plasma density gradient but also on parameters of a laser pulse and particularly on its intensity and the pulse duration. As it results from our numerical simulations, the swelling factor (its maximal value) decreases when the plasma density gradient λ/L_n, the intensity or the pulse duration increase (within the ranges of these parameters shown in the figures). For instance, at $L_n/\lambda = 1$, $I_L = 10^{17}$W/cm^2, the swelling factor decreases from $S \approx 2$ for $\tau_L= 0.2$ ps down to $S \approx 1.3$ for $\tau_L= 2$. Thus, at high values of the above three parameters (λ/L_n, I_L, τ_L), the forward-directed force from the usual light pressure predominates the backward-directed one and, as a result, the velocities and current densities of forward-emitted ions are considerably higher than the ones for backward-emitted ions. The decreasing swelling factor is also the main reason for the faster increase in υ_f and j_f (than υ_b and j_b, respectively) when the laser intensity increases (Fig. 4).

Fig.3

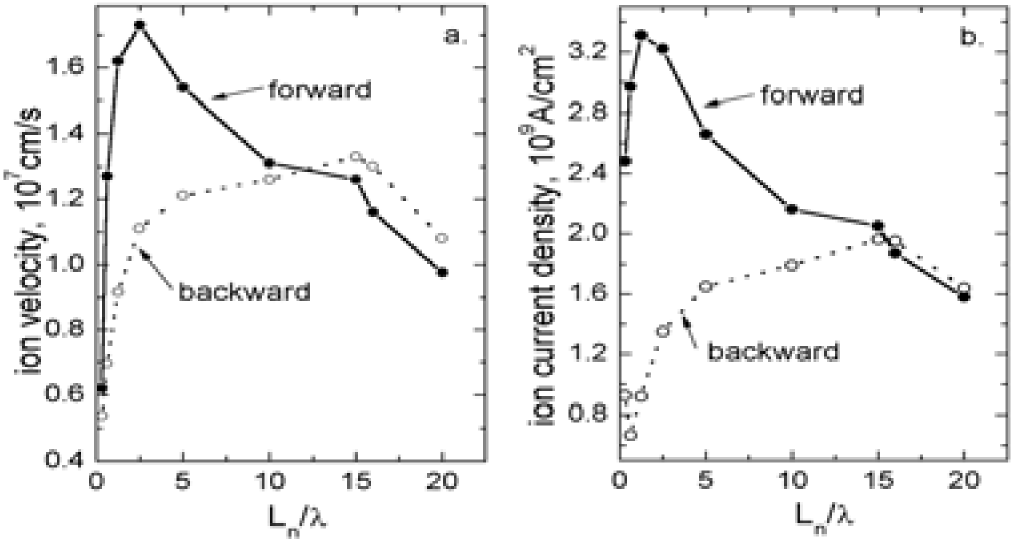

Fig.3. The dependencies of the maximum ion velocities (a) and the maximum ion current densities (b) on the plasma density gradient scale length. τ_L *= 1 ps,* $I_L = 10^{16}$ *W/cm*^{2}

Fig.4

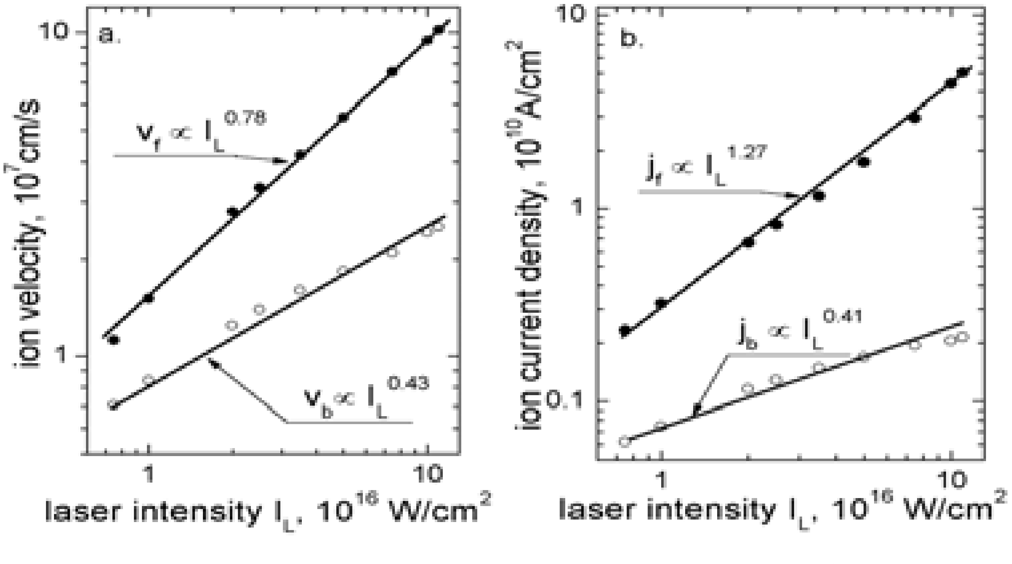

Fig.4. The maximum ion velocities (a) and the maximum ion current densities (b) for backward-emitted (υ_b*,* j_b*) and forward-emitted (*υ_f*,* j_f*) ions as a function of laser intensity,* τ_L *= 1,* $L_n/\lambda = 1$*.*

In conclusion, the numerical simulations based on the two-fluid hydrodynamic plasma model confirmed both qualitatively and quantitatively the idea of production of ultrahigh- current-density ion beams with the use of ponderomotive forces induced at the skin-layer interaction of a short laser pulse of subrelativistic intensity with a thin inhomogeneous plasma layer. The results of the computations were found to be consistent with the simplified theory and measurements.

Fig.5

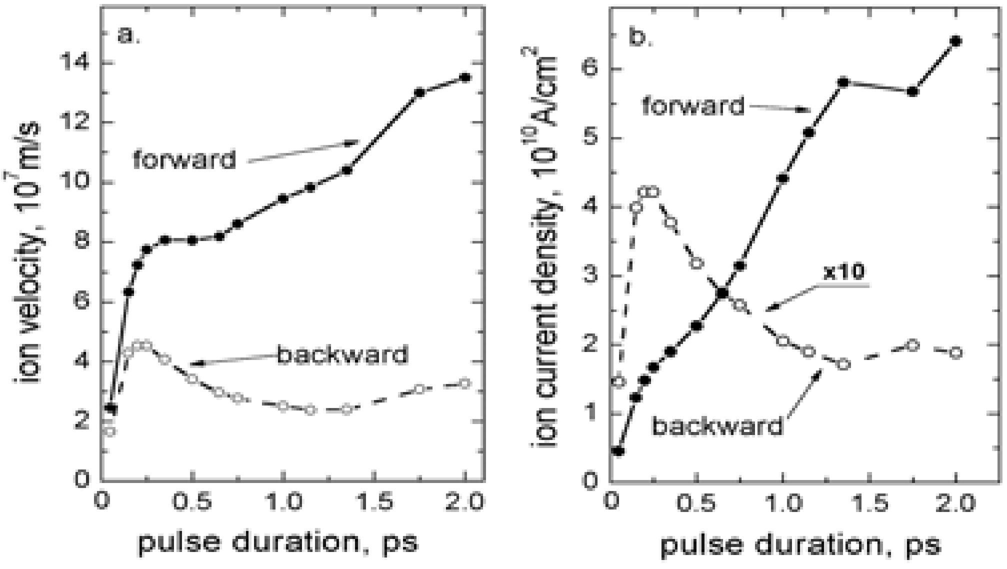

Fig. 5. The maximum ion velocities (a) and the maximum ion current densities (b) as a function of the laser pulse duration. $I_L = 10^{17} W/cm^2$, $L_n/\lambda = 1$.

4. AIMS FOR LASER DRIVEN FUSION ENERGY

The most expensive attempts to harness fusion energy of a clean, very low cost, safe and nearly infinite energy source on earth began 70 years ago with the discovery of the nuclear reactions of isotopes of hydrogen discovered by Mark Oliphant, Paul Harteck and Lord Rutherford [46]. These reaction were absolutely different form the usual nuclear reactions where the colliding nuclei hat to energies of several MeV to reach distances of about fm. For the fusion reactions, only keV energies were necessary and the reactions happened in distances about 100 times the nuclear size. The initial hope of Oliphant [46], to produce fusion energy from particle beams on targets was fully destroyed by Spitzer in 1950 by indicating that the beam of deuterium (and tritium) irradiating a cold target low their energy to heat electrons and less the 1/300 goes into the desired fusion reactions. Therefore, one had to confine the plasma by magnetic fields to equilibrium temperatures of several dozens of million degrees such that electron collision do not count and only fusion reaction will of DT will lead to the desired energy gain.

This argument of Spitzer was fully correct in logics, mathematics and physics. But it was wrong since it was linear physics [8,9]. Nonlinear physics can change linear statements from yes to no form right to wrong (not only by gradual corrections) what was drastically experienced with the discovery of the laser. Fusion energy driven by lasers of related to very intense ion beam was the new im after 1960 [46]. Nevertheless magnetic confinement fusion (MCF) is still dominating though the highest fusion ain ever observed within about 1 second operation of the JET in Culham/England was producing 16 MF fusion energy fonr a 40:60 DT tokamak by irradiation 21 MW neutron deuterium beam of 60 MeV and 3 MW ECR, a gain of 66% [46,47] This experiment may then be categorized as a beam fusion experiment [46,47]. The planned ITER tokamak for more then \$10Billions is expected in 2015 to work for 500 seconds and to produce 500 MW thermal fusion energy at an input of 500 MW electrical energy (gain less than 33%) [48] however with a high temperature plasma target following mostly the linear Spitzer theorem.

Laser fusion with inertial confinement (ICF) reached similar high gains [47] and the goal was experimentally confirmed by compression and ignition of DT pellets using 50 MJ x-radiation pulses in the Centurion-Halite experiments (see Broad [8]). With more sophisticated laser beams the irradiation by 10 MJ laser pulses of ns dureation was elaborated [48]. One disappointing result was that the compression of deuterated polyethylene by laser to 2000 times the solid state density [31] arrived at rather low temperatures of 3 Million Kelvin only. To overcome this problem, the fast ignitor (FI) was invented [40] where a ns laser pulse compresses the DT fuel to few thousand times the solid state and an additional heating follows with the new typ of PW-ps laser pulses according to Mourou [1].

It should be mentioned that the many MJ laser systems as NIF and the MJL [46] with ns laser pulses may not only be used for studying other nuclear fusion reactions, that the solution of a power station by compression to several 1000 solid state and temperatures of several hundred eV are sufficient in a one step process to produce very high gain fusion energy using the scheme of volume ignition [47]. This is a scheme of a fusion reactor based on present days physics where there is no physics limitation that the necessary technological development can lead to a competitive solution of a power station.

5. PW-ps LASER PULSES FOR CONTROLLED IGNITION OF SOLID DT

The here presented results of the TW or PW laser pulses of ps duration may open an alternative option for laser fusion where the complicated compression of the DT fuel to several 1000 times the solid state may be avoided and the irradiation on uncompressed solid state DT may lead to the solution of the fusion power station as a possible option for a much lower cost competitive technological solution.

The result (8) of ion current densities above 10^{10} A/cm^2 for ion energies above 50 keV up to higher values from fast blocks driven into a target by the nonlinear (ponderomotive) force at laser interaction may permit an application to beam fusion as discussed before [49,50]. Light ion beams for igniting nuclear fusion reactions in uncompressed solid deuterium-tritium targets were considered since years and the necessary conditions turned out to be far above the available technology for generating the ion beams. Nevertheless this scheme was studied in various experiments [51]. The difficulties with the necessary conditions were the following two limits. The ion beam current density j had to be above the threshold [52]

$$j > j^* = 10^{10} \text{ A/cm}^2 \tag{9}$$

and the energy density the for generating a reaction front (flame propagation) into uncompressed solid DT was derived theoretically [53] to be above the threshold

$$E^* = 4\text{x}10^8 \text{ J/cm}^2 \tag{10}$$

Even more pessimistic higher thresholds E* were considered which however may be upper bonds only as long the very extensive details for the derivation of the threshold (18) are not found to be incorrect.

It may be even that the value (10) is too pessimistic as there were indications from the theory how the interpenetration of the igniting energetic ions into the cold uncompressed DT fuel may reduce the threshold E* to [54]

$$E^*_1 = 2\text{x}10^7 \text{ J/cm}^2 \tag{11}$$

How unexplored these beam fusion conditions are, may be seen from the experiments [55,56] where 2 MeV electrons of an estimated current density of 3x10^6 A/cm^2 interacting with a CD_2 target showed a penetration of 0.3 cm only. The single electron penetration would have been more than 40 times longer. The disagreement with the Bethe-Bloch-Bohr binary collision theory for the stopping length could be clarified by applying the collective interaction process which fully reproduces the measured 0.3 cm [55]. The collective interaction was initially studied by Gabor 1953 [57] and based on the independently derived theory [58] for the successful explanation [56] of the experiments [55]. Such reduction of the collective stopping length combines with the not yet applied anomalous plasma resistivity [8, Sect. 2.6] and electric double layer effects with reduced thermal conductivity [59] points into the further decrease of the threshold (11).

Thanks to the recent results on interaction of clean TW-ps laser pulses it was possible to show experimentally [11], Eq. (8), that the rather extremely high threshold j*, Eq. (9), for ion beam fusion has been fulfilled [45,50]. The skin layer interaction mechanism accelerates a plasma layer or block initially of 30 wave length width and several vacuum wave lengths thickness with a critical density of 10^{21} electrons/cm^3 highly directed against the laser light whose velocity from 20 keV/nucleon at 8x10^{16} W/cm^2 intensity could be understood in the case of a DT plasma to be 1.23x10^8 cm/s. This results in a block motion with an ion current density at the target of 1.9x10^{10} A/cm^2.

From this result it was concluded that the compressing block may be used as requested for light ion beam fusion for a power station. A 10 kJ laser pulse could then produce more than 10 MJ fusion energy where the exclusive use for the controlled reaction was confirmed by a declassification procedure by the authorities involved [50,60].

For the physics – within many more problems to be clarified – it has to be shown that at least the condition (9) has to be fulfilled where we are aware that this even may be considered as a pessimistic conclusion in view of the not yet exhausted theory about the threshold E* towards lower values. For the compressing block, the whole maximum quiver energy of the electron is converted into translation energy of the ions. The aim for the DT interaction, we use the oscillation energy of 80 keV of the resonance maximum of the DT reaction may not necessarily be the best choice. Since this is close to the [9] relativistic threshold intensity I_{rel} we have to use the general case

$$\varepsilon_{osc} = m_o c^2 \left[(1 + 3SI_{vac}/I_{rel})^{1/2} - 1\right] \tag{12}$$

where the maximum intensity $I_{max}=SI_{vac}$ due to the dielectric swelling near the critical density is expressed by the factor S with the laser intensity I_{vac} in vacuum at the target surface.

For the general analysis we have to be flexible about the chosen values of the applied maximum (dielectrically swelled) oscillation energy $\square_{osc}$ into the translation DT ion energy $\square_{trans}$ in adjustment to fusion cross sections. We further let open the value of the energy flux density $E^* = I_{vac}\,\tau_L$ for the reaction conditions (10) or (11) or possibly even a lower value depending on the future research to find the correct value E* where the laser pulse duration t_L will have to be in the range of ps. According to our numerical studies [43] in agreement with summarizing estimations, this value could well be a few ps. From the relations (11) and

$$I_{vac} = E^*/\tau_L \tag{13}$$

we arrive at the function for the laser wave length

$$\lambda(\varepsilon_{\square\square\square\square\square}, E^*, \tau_{L,}S) = \left[\tau_L\, I^*_{rel}/(3SE^*)\right]^{1/2} \left\{\left[(\varepsilon_{trans}/m_o c^2) + 1\right]^2 - 1\right\}^{1/2} \tag{14}$$

Using as a special case $\tau_L = 3$ps, $E^* = 2\mathrm{x}10^7$ J/cm^2, $\varepsilon_{trans} = 80$ keV, we arrive at

$$\lambda = 0.516/S^{1/2}\ \mu\mathrm{m} \ (15)$$

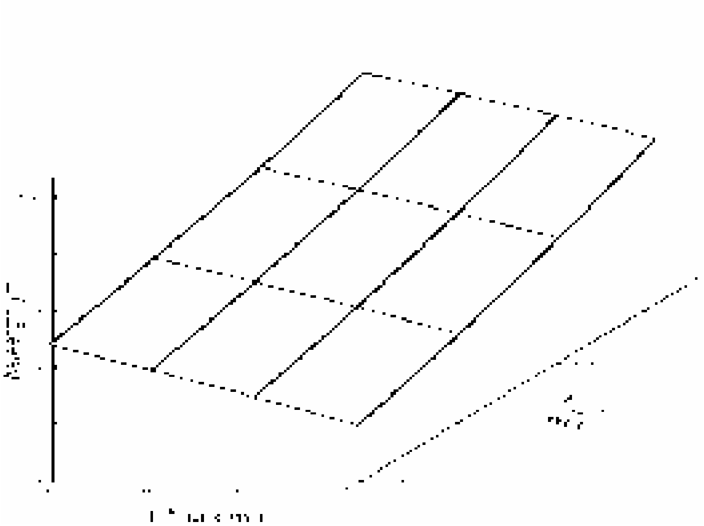

Fig. 6. Relation between the laser wave length the aimed ion energy ε_{trans} in multiples of $m_o c^2$ and the necessary energy flux density for ignition of uncompressed DT following Eq. (14) for S = 1 and a laser pulse length of 3 ps.

The nonlinear force driven two-block skin layer interaction model works for swelling S considerably large than 1, as it was the case automatically from the detailed analysis of the measurements [6,11] with S = 3. The lowest possible case with S = 1, is that without any dielectric swelling where the whole laser pulse energy is transferred as in the simple case of radiation pressure [9] to the absorbing plasma. We conclude that the conditions of the kind of (10) or (11) could well be fulfilled for the ignition of uncompressed solid DT fuel when applying shorter laser wave length than that of the neodymium glass laser which are well in the reach of present technology. For the pessimistic case of Bobin and Chu [53], the numerical factor in (15) is 0.105 such that with S =1 just the borderline of higher harmonics CPA or of excimer lasers would be covered. Further research on lower values of E* and numerical studies for a little bit longer laser pulses may further relax the conditions, and longer laser wave lengths would be possible. No discrepancy was found in the detailed analysis [53] when followed up recently [61]. Fig. 6 shows the dependence of the necessary laser wave length for a pulse length of 3 ps and swelling S =1 which one needs for a desired ion translative energy in multiples of m_oc^2 (m_o is the rest mass of the electron) if the threshold E* is given. Maybe there is a narrow gap for successful conditions as A. Sakharov realized [62].

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