Dielectric magnifying of plasma blocks by nonlinear force acceleration with delayed electron heating

Rasoul Sadighi-Bonabi,[1] Elnaz Yazdani,[2] Yu Cang,[3] and Heinrich Hora[4]
[1]Department of Physics, Sharif University of Technology, P.O. Box 11365-9567, Tehran, Iran
[2]Department of Physics, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran and Laser and Optics Research School P.O. Box 14155-1339, Tehran, Iran
[3]Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China
[4]Department of Theoretical Physics, University of New South Wales, Sydney 2052, Australia

(Received 7 July 2010; accepted 15 September 2010; published online 9 November 2010)

Specific studies were performed in order to increase the thickness of laser generated directed space charge quasineutral plasma blocks with anomalously high ion current densities above 10^{11} A/cm^2. This may lead to an alternative scheme of laser driven fusion with the irradiation of petawatt-picosecond laser pulses. Initial electron densities were used with Rayleigh profiles, because these are unique for inhomogeneous plasmas for undistorted acceleration at very low reflectivity until thermal absorption processes disturb these ideal conditions. Numerical hydrodynamic results based on a genuine two-fluid code are presented to optimize the block generation for possible fast ignition and details show the delay of thermal exchange between the ion and electron plasma fluid. © *2010 American Institute of Physics*. [doi:10.1063/1.3497009]

I. INTRODUCTION

In recent years, the developments of laser pulses were highly motivated by the scheme of the fast igniter[1] for applications in nuclear fusion of deuterium-tritium. Recent rapid advancement in the development of intense laser systems in the production of quasimonoenergetic electrons currently boosts the use of such devices in producing energetic particle beams.[2] Studying the interaction of such advanced laser systems with plasma in various conditions is discussed.[3] Laser pulses between terawatt and a few petawatt power with a few picoseconds and even shorter duration times were applied.[4] Based on various observations, a rather rarely reported anomaly was measured. Instead of the usually emitted very intense and hard x-rays, only very much lower intensities and softer x-rays were measured[5] and instead of the usually expected 22 MeV fast copper ions, only half MeV maximum ion energy was measured, where the ion number did not depend on the laser pulse energy.[6] This was explained based on the fact that these anomalous measurements were done with exceptionally clean laser pulses where any prepulse was suppressed by a factor 10^8 (contrast ratio) up to about 10 ps before the main pulse arrived at the target. In these conditions, it can be concluded that no relativistic self-focusing could have been involved.[7]

All this could be explained by the acceleration of the very fast ions as a block from the skin layer surface in full agreement with the acceleration by the nonlinear (ponderomotive) force.[8] This skin layer acceleration by the nonlinear force (SLANF) was confirmed experimentally from the highly directed space charge quasineutral plasma blocks with directed current densities above 10^{11} A/cm^2 of ions up to 100 keV.[7,8] The involved mechanisms[8–10] are also important for energy transport in overdense plasmas[11] based on a special analysis.[12]

The nonlinear driven plasma blocks may permit an alternative approach for laser fusion based on the hydrodynamic analysis by Chu[13] where a fusion reaction wave was studied to be produced by irradiating uncompressed solid state density deuterium-tritium. The result for this side-on ignition, however, showed[13] that the most exorbitant amount of energy flux density E^* of more than 4×10^8 J/cm^2 is needed. This may be available in the near future, thanks to the technology of the petawatt-picosecond laser pulses and thanks to the anomaly[7,8] of the laser generated very high ion current densities. For estimating conditions of this laser fusion scheme, the problem of E^* was studied in view of the relaxation of the ignition conditions[4] due to phenomena discovered after the early analysis by Chu.[13] The other problem is how to produce sufficiently deep plasma blocks. One option is conical guiding of the plasma blocks;[8] another is to find conditions for generating thick plasma blocks from the beginning.

This work focuses on the plasma-optical problem and how the initially accelerated blocks may be produced with a higher thickness or more depth by using better selected optical properties in the laser irradiated inhomogeneous plasma layers. This can be achieved if an appropriate initial plasma density is produced according to the theory of the Rayleigh density profiles.

II. PROBLEMS OF OPTICAL PROPAGATION IN INHOMOGENEOUS PLASMAS

One of the fundamental problems of wave propagation in plasmas is the fact that these plasmas are nearly always inhomogeneous. All this is defined with the solution of the ordinary linear differential equation for the spatial part of the electric field amplitude E(x) of the electric field **E** depending on the one dimensional spatial coordinate x combined with that of the magnetic field **H** by Maxwell's equations,

$$(d^2/dx^2)E(x) + (\omega/c)^2 n(x)^2 E(x) = 0, \quad (1)$$

where ω is the radian frequency of the laser, c is the vacuum speed of light, and n is the real part of the refractive index of the plasma, given by $\mathbf{n}(x)^2 = 1-(\omega/\omega_p)^2/(1+i\nu/\omega)$ using the plasma frequency $\omega_p = (4\pi e^2 n_e(x)/m)^{1/2}$, and the spatially and temperature dependent collision frequency ν in the plasma. e is the charge, m is the mass, and n_e is the density of the electrons in the plasma. The wave equation (1) is trivial if n_e is constant (homogeneous plasma) where the solutions of Eq. (1) are given by elementary functions cos(x), sin(x), or exp (ix). But for x-dependent n(x), as in all the inhomogeneous plasmas, the solution of Eq. (1) is very complicated and contains a substantial part of mathematics of the 19th century. For the general case of plasmas with spatial variation of the electron distribution, $n_e(x)$, special series of higher functions have to be used. In this situation, it was rather unique that Rayleigh[14] found a solution for the wave equation (1) for an inhomogeneous medium, if the refractive index is given by $n = 1/(1+\alpha x)$ with a constant α. The solutions were exactly expressed by elementary functions with amplitude E_o,

$$E(x) = (1 + \alpha x)^{1/2} E_o \times \exp\{\pm (i/2)[(2\omega/c\alpha)^2 - 1]^{1/2} \ln(1 + \alpha x)\}. \quad (2)$$

With these exact solutions, the reflection between a homogeneous and an inhomogeneous Rayleigh medium could be solved exactly, and it was clarified by Hora[15] that there are only two exact solutions in the inhomogeneous optical medium for a wave moving into the direction of +x and one to −x. There were *no internal reflections* as it was wrongly suggested from the many-layer approximation (see. Ref. 17, Sec. 7.3). The Rayleigh medium has a special importance when studying the nonlinear (ponderomotive) forces generated by a laser field in plasmas. It was known from *electrostatics* that electrons can be moved by a ponderomotive force if there are gradients in the electric field **E** given by $-\nabla \mathbf{E}^2$. It was the merit of Weibel[16] to demonstrate that the same forces on electrons in vacuum appear also time averaged in the *high-frequency* fields of microwaves. The evaluation of these forces in plasmas including the inhomogeneous dielectric properties resulted in a nonlinear force density[17] after subtracting gas dynamic, thermokinetic forces. The force can be reduced and time averaged and with approximately using real part values of **n**,

$$\begin{aligned}\mathbf{f}_{NL} &= -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) \\ &= (\mathbf{n}^2 - 1)\nabla \mathbf{E}^2/(8\pi) \\ &= -(\omega_p/\omega)^2 (\partial/\partial x)(E_v{}^2/n)/(16\pi).\end{aligned} \quad (3)$$

Here, E_v, is the amplitude of the electric field of the laser in vacuum. Within the plasma, the square of the electric field is increased by a swelling factor $S = 1/n(x)$. With respect to the results of the Rayleigh profiles, the main limitation is that propagating waves require an oscillating exponential function. This is fulfilled as long as $4\omega^2/(c^2\alpha^2) - 1 > 0$ and where the limit for $\alpha < \alpha_o = 1.1 \times 10^5\ \text{cm}^{-1}$ is given for neodymium glass lasers. For α higher than the threshold α_o, the solution in Eq. (2) is exponentially decaying with a total reflection at the boundary of the vacuum and the plasma.

In the following, we shall consider mostly cases where $(\mathbf{n}^2 - 1) = -n_e/n_{ec}$ is close to −1 where n_{ec} is the critical density with $\omega = \omega_p$. Apart from the fast oscillating part in Eq. (2) where the absolute value of the exponential function is equal or less than 1, the ponderomotive action as determined by the Rayleigh refraction is constant,

$$\nabla \mathbf{E}^2 = E_0{}^2 (d/dx)(1/n) = \alpha. \quad (4)$$

A consequence is that the whole plasma is then accelerated as an undistorted block. This property of the Rayleigh profile with respect to the nonlinear (ponderomotive) force is very significant and important to uniformly generate fast moving plasma blocks for different applications.

The result of the undistorted plasma blocks with thickness of about 20 times the vacuum wavelength by laser irradiation of Rayleigh density profiles was reported in one numerical hydrodynamic fluid studies[18] (see Ref. 17, Sec. 10.5) of nonlinear force acceleration in plane geometry. But this was only many years later to be confirmed in the first exact measurement by Sauerbrey.[19] The measured acceleration of plasma blocks was about $10^{20}\ \text{cm/s}^2$ in agreement with predictions by the nonlinear force.[8,17] This was only possible because of the then available terawatt-picosecond laser pulses with a contrast ratio above 10^8 to avoid relativistic self-focusing.[8] The computations confirmed that the thickness of the skin layer in the Rayleigh profile with the appropriately selected α-value was increased by the swelling factor $S = 1/n$. This value could easily be higher than 20 times even with inclusion of the collision frequency.[17,18]

This was all essential in the clarification of the anomaly for terawatt-picosecond laser pulse interaction with targets as a SLANF process which was shown before (Fig. 1 of Ref. 8). A neodymium glass laser pulse of $10^{18}\ \text{W/cm}^2$ irradiated a deuterium plasma of initially 100 eV temperature and a Rayleigh profile with $\alpha = 2 \times 10^4\ \text{cm}^{-1}$. At the interaction time of 1.5 ps, the electric field **E** of the laser was so strongly swelled that the laser field energy density was more than 15 times higher than that in the vacuum. In the same way, the thickness of the skin layer was increased by a similar factor and a deuterium plasma block of more than 15 vacuum wavelength depth was moving against the laser light nearly undistorted with velocities up to a few $10^9\ \text{cm/s}$. A similar block was moving into the plasma below the critical density.

It is important to note that the hydrodynamic codes describe the macroscopic drift velocity of the ions while their thermal energy of motion determines their temperature. The change of this temperature by pressure into macroscopic motion is given by the hydrodynamic conservation equations. In the hydrodynamics of the earlier studies,[8,17,18] plasma with collisions and time delays between heating of the electrons and equipartition to ions was included in the same way as in the following computations.

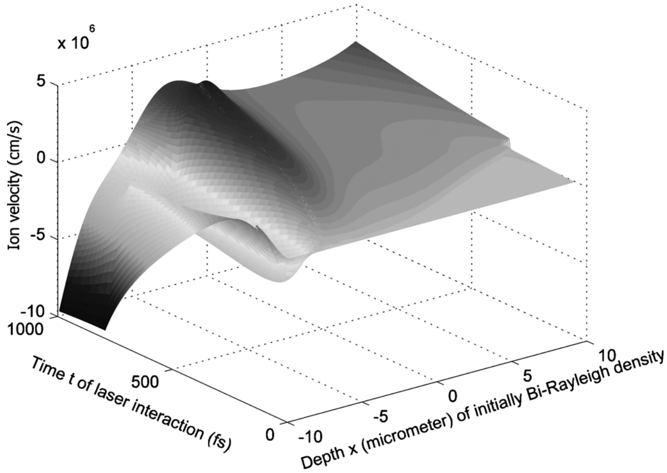

FIG. 1. Ion velocity within an initially bi-Rayleigh ($\alpha = 9.59 \times 10^3$ cm^{-1}) deuterium plasma with initially zero velocity and with 100 eV initial temperature located between -10 and $+10$ μm at neodymium glass laser irradiation from the left hand side of 2×10^{16} W/cm^2 intensity during the time between 0 and 750 fs.

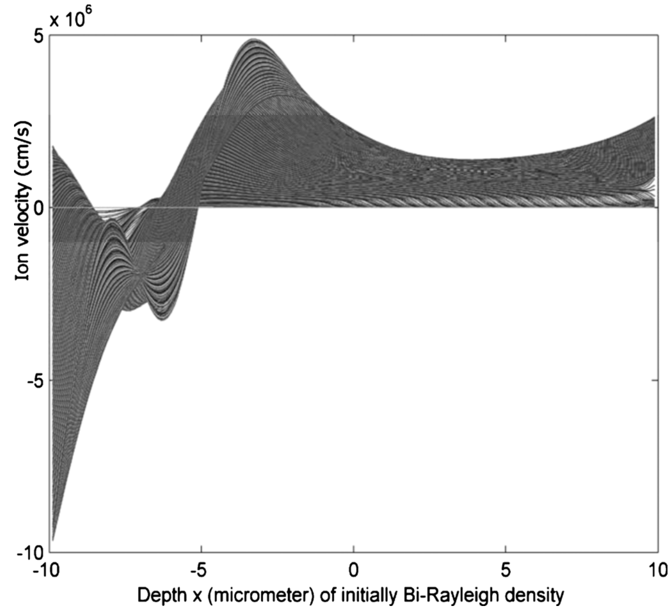

FIG. 2. Same as Fig. 1 with overdrawn curves.

III. NUMERICAL STUDY USING THE GENUINE TWO-FLUID HYDRODYNAMICS

In order to clarify the selection of parameters for initial density profiles, computations were performed mostly with a Rayleigh type for the initial density including initial temperatures and initial zero macroscopic velocities and the time dependence of the interaction with the laser pulses. The critical ion density n_{ec} was 10^{21} cm^{-3}. In these cases, the nonlinear force dominates the thermokinetic forces during the short interaction time for achieving thick plasma blocks. Attention was especially given for producing a thick plasma block directed inside the plasma in the direction for the laser propagation for the conditions described before (see area A in Fig. 6 of Ref. 8).

The advanced and very general hydrodynamic interaction code was used as derived by a genuine two-fluid treatment.[20] In this case, the double layer processes at the caviton generation[21] resulted in a plasma block of five vacuum wavelength thicknesses moving against the laser light being compensated by the block moving into the target. Another two-fluid computation was used before analyzing the partial standing wave generation[22] while the present analysis is to find conditions to avoid the subsequent density rippling. Another formulation of a genuine two-fluid code was established[23] to show the plasma block generation when the laser pulse is hitting an initially linearly increasing density ramp.

The following results are using the earlier described code[23] which is now applied for the laser interaction of the initial density with a Rayleigh density profile or with slight modifications. For comparison with the earlier one-fluid computations[17,18] and a first evaluation,[24] more detailed results are presented here for a laser intensity of 2×10^{16} W/cm^2 and laser pulse durations of 500 and 750 fs. This time restriction is appropriate for the study of an initial plasma thickness of about 20 μm only for the nonrelativistic code. The initial plasma density given by the ion density n_i (at time $t=0$) depends on the plasma depth x (in centimeter) for bi-Rayleigh profile for increasing from $x = -10$ μm to $x=0$ and decaying from there up to $x=10$ μm. The value of $\alpha = 0.959 \times 10^4$ cm^{-1} was chosen for similarity with other numerous cases.

Figure 1 shows the resulting ion velocity when the initial temperature of the plasma was chosen to be 100 eV and the laser was acting between the time 0 and 750 fs. Figure 2 shows the overdrawing of the three dimensional diagram of Fig. 1. In order to show the heating process of the electrons and ions, we show a case with the same parameters as before but selecting 10 eV as initial temperature to better observe the temperature fluctuations for a 300 fs long interaction. Figure 3 shows the result of the ion temperature and Fig. 4 shows that of the electron temperature.

For a qualitative overview, the following results are added for the same laser intensity, same α-value, and same

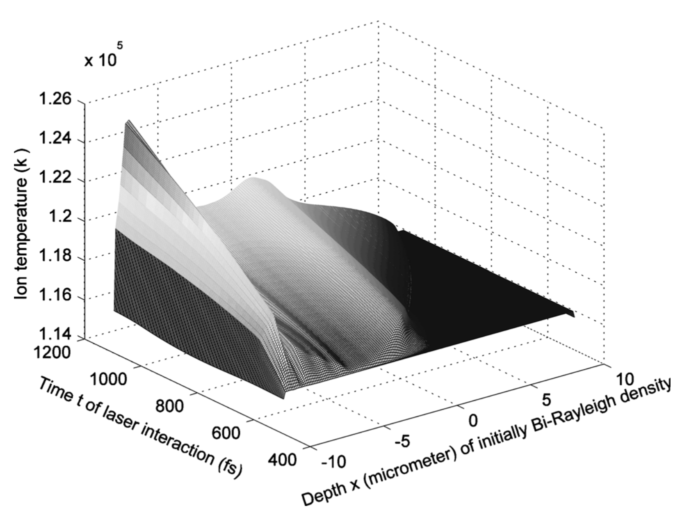

FIG. 3. Ion temperature for the same conditions as in Fig. 1 but at 10 eV initial temperature and laser interaction between 500 and 800 fs.

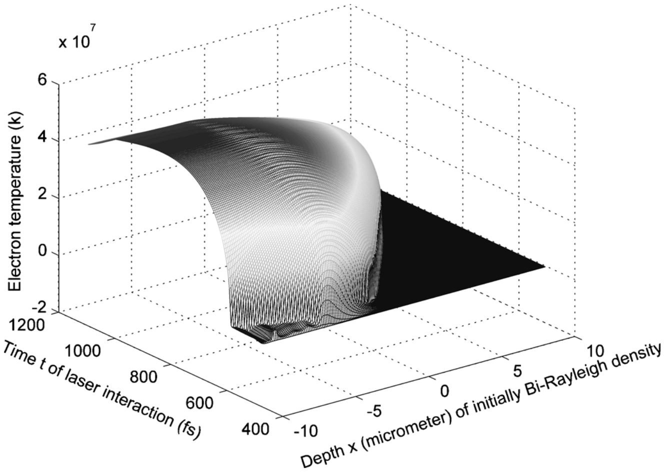

FIG. 4. Electron temperature for the case of Fig. 3.

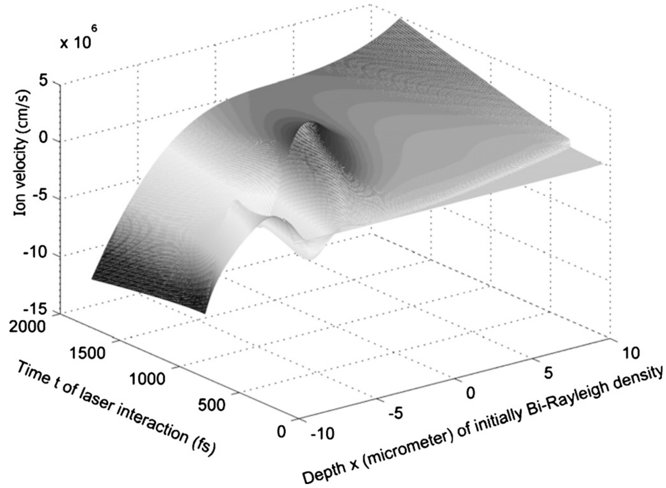

FIG. 6. Ion velocity profile for 1750 fs interaction time as in Fig. 5.

initial temperature and initial bi-Rayleigh profile of deuterium plasma. Figure 5 shows the print-out of the development of the electromagnetic laser energy density in the plasma for 750 fs interaction time. Figure 6 shows the ion velocity profiles for a 1750 fs interaction where at early times the laser field had developed an intensity minimum near the entrance in the plasma automatically from the general numerical solution of the generated field. Figure 7 shows the ion density profile at 500 fs interaction where the generation of the caviton near the entrance of the laser field can be seen as known from earlier computations.[21]

IV. DISCUSSION OF THE RESULTS

For the case of 750 fs interaction, the propagation of the laser field into the plasma can be seen from the wedges in Fig. 1 for the first 300 fs, where the ion velocity is zero up to the end of the plasma at +10 μm. This corresponds to one half of the vacuum speed of light and it expresses a dielectric swelling by a factor 2 by which the factor of the speed of light in the plasma is being reduced. Then the light is switched off at 750 fs, and the plasma moving against the laser light can be seen (negative velocities) while the maximum velocity for the motion into the plasma has been reached with subsequent spreading of the velocity profile at the free motion of the generated plasma block. The fact that there is still a little increase of the velocity at x=+10 μm may be understood from this spreading process. In any case, during the interaction, the laser intensity is high enough at the end of the plasma, such that the stronger (negative) density gradient there causes the push of the plasma along the direction of the laser light.

Figure 2 shows a maximum ion velocity of 5×10^6 cm/s related to the interaction time of 750 fs. This corresponds to an acceleration of

$$a = 6.6 \times 10^{18} \text{ cm/s}^2. \tag{5}$$

This may be compared with the theoretically expected value of the acceleration as done before[8] and for the acceleration measured at higher intensity by Sauerbrey.[19] For the acceleration into the plasma, the amplitude of the laser field is

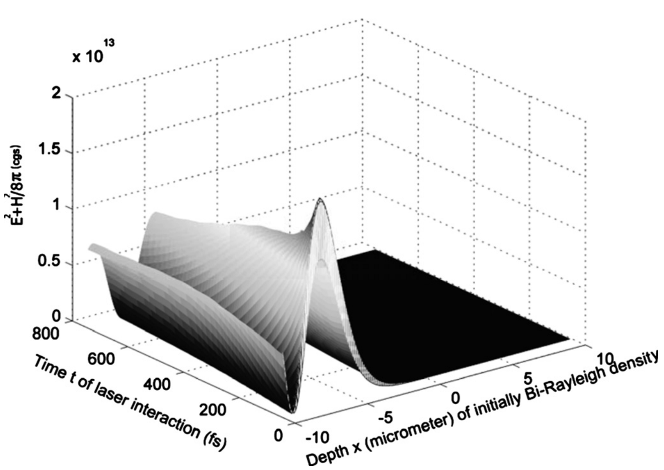

FIG. 5. Electromagnetic field energy density $(\mathbf{E}^2+\mathbf{H}^2)/8\pi$ in cgs of the laser in the plasma at 750 fs interaction time for same conditions as in Fig. 1.

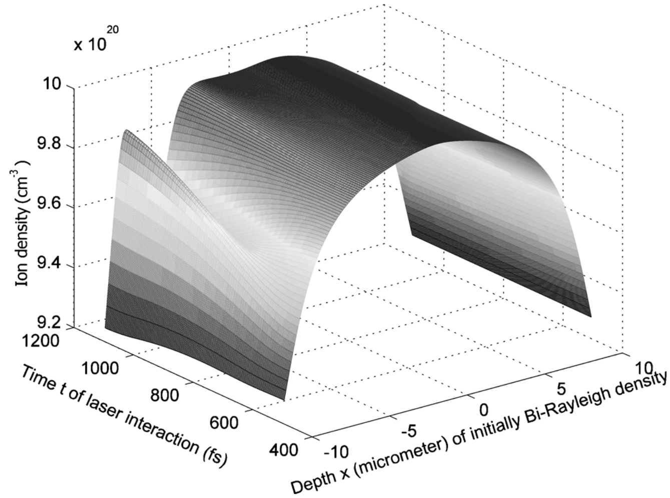

FIG. 7. Ion density profile for 500 fs interaction for same conditions as before.

taken as E_o^2S by using the swelling factor S and the vacuum amplitude of the laser field. The density ρ of the deuterium at critical density defines the force density according to Eq. (4),

$$\rho a = (\partial/\partial x)E_o^2S/(8\pi), \tag{6}$$

where approximately the value is $\partial x = 3.3\ \mu m$. For the laser intensity $2\times10^{16}\ W/cm^2$, one arrives with $S=2$ at an acceleration of $a=6.44\times10^{18}\ cm/s^2$ in rather good agreement with the results in Eq. (5) of the computation.

The heating processes following Figs. 3 and 4 may be followed up and at least qualitatively the genuine two-fluid code[20,23] is correctly describing the delays of heat transfer from the electrons to the ions while the main energy transfer to the ions is given by the nonlinear force driven nonthermal plasma dynamics. We note that the laser action is between 500 and 750 fs. There is indeed a heating of the electrons by converting the quiver motion into heat by collisions up to about 4 keV with short delay as expected (see p. 417 of Ref. 25), decaying from 750 fs after the laser action, but due to the very much longer equipartition time being completely included in the code based on the classical collisions, the ions are heated by the electrons only marginally. The ion heating shown in Fig. 3 is dominated by the adiabatic dynamic processes of the acceleration by the nonlinear forces. This works even after 750 fs after the ion fluid has been brought into motion by the nonlinear force.

V. CONCLUSION

The scheme of side-on ignition of solid state density deuterium-tritium for fusion energy production following Chu[13] and an updated reduction of the threshold[4] needs the generation of highly directed space charge neutral plasma blocks. This can be achieved by nonlinear (ponderomotive) force acceleration at laser interaction by extension of the effective skin layer using special profiles of dielectric plasma properties. Using the genuine two-fluid plasma hydrodynamics, this block generation leads to thicknesses of a large number of vacuum wavelengths. The properties of the results of computations are compared with the expected theoretical values confirming the detailed inclusion of plasma dynamics in the computations. These can be used in examples to show how the laser heating of the electrons by collisions arrives at very different temperatures during the processes in less than picosecond duration because of the comparably delayed equipartition process for heating of the ions. At the studied high laser intensities, the nonlinear force dominates the nonthermal transfer of laser energy in the directed ion motion.

[1] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, and M. D. Perry, Phys. Plasmas **1**, 1626 (1994).
[2] R. Sadighi-Bonabi and Sh. Rahmatollahpur, Phys. Plasmas **17**, 033105 (2010); Phys. Rev. A **81**, 023408 (2010); R. Sadighi-Bonabi and M. Etehadi-Abari, Phys. Plasmas **17**, 032101 (2010).
[3] R. Sadighi-Bonabi, M. Habibi, and E. Yazdani, Phys. Plasmas **16**, 083105 (2009); R. Sadighi-Bonabi, E. Yazdani, M. Habibi, and E. Lotfi, J. Opt. Soc. Am. B **27**, 1731 (2010).
[4] H. Hora, B. Malkynia, M. Ghornneviss, G. H., Miley and X. He, Appl. Phys. Lett. **93**, 011101 (2008); H. Hora, G. H. Miley, M. Ghoranneviss, B. Malekynia, and N. Azizi, Opt. Commun. **282**, 4124 (2009); H. Hora, G. H. Miley, M. Ghoranneviss, B. Malekynia, N. Azizi, and X.-T. He, Energy Environ. Sci. **3**, 479 (2010).
[5] P. Zhang, J. T. He, D. B. Chen, Z. H. Li, Y. Zhang, J. G. Bian, L. Wang, Z. L. Li, B. H. Feng, X. L. Zhang, D. X. Zhang, X. W. Tang, and J. Zhang, Phys. Rev. E **57**, R3746 (1998).
[6] J. Badziak, A. A. Kozlov, J. Makowski, P. Parys, L. Ryc, J. Wolowski, E. Woryna, and A. B. Vankov, Laser Part. Beams **17**, 323 (1999).
[7] H. Hora, J. Badziak, F. P. Boody, R. Hopfl, K. Jungwirth, B. Kralikova, J. Krasa, L. Laska, P. Parys, V. Perina, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied, J. Wolowski, and E. Woryna, Opt. Commun. **207**, 333 (2002).
[8] H. Hora, J. Badziak, M. N. Read, Y.-T. Li, T.-J. Liang, Y. Cang, H. Liu, Z.-M. Sheng, J. Zhang, F. Osman, G. H. Miley, W. Zhang, X. He, H. Peng, S. Glowacz, S. Jablonski, J. Wolowski, Z. Skladanowski, K. Jungwirth, K. Rohlena, and J. Ullschmied, Phys. Plasmas **14**, 072701 (2007).
[9] C. T. Zhou, X. T. He, and M. Y. Yu, Appl. Phys. Lett. **92**, 151502 (2008).
[10] J. Badziak, S. Glowacz, S. Jablonski, P. Parys, J. Wolowski, and H. Hora, Laser Part. Beams **23**, 142 (2005).
[11] C. T. Zhou and X. T. He, Appl. Phys. Lett. **90**, 031503 (2007).
[12] C. T. Zhou, M. Y. Yu, and X. T. He, Laser Part. Beams **25**, 313 (2007).
[13] M. S. Chu, Phys. Fluids **15**, 413 (1972).
[14] L. Rayleigh, Proc. R. Soc. London **11**, 51 (1880).
[15] H. Hora, *Jenaer Jahrbuch* (Carl Zeiss, Jena, 1957), pp. 131–144.
[16] E. Weibel, J. Electron. Control **5**, 435 (1957).
[17] H. Hora, *Plasmas at High Temperature and Density* (Springer, Heidelberg, 1991).
[18] V. F. Lawrence, "Momentum transfer of laser radiation in inhomogeneous dielectrics," Ph.D. thesis, University of New South Wales, 1978.
[19] R. Sauerbrey, Phys. Plasmas **3**, 4712 (1996).
[20] P. Lalousis and H. Hora, Laser Part. Beams **1**, 283 (1983).
[21] H. Hora, P. Lalousis, and S. Eliezer, Phys. Rev. Lett. **53**, 1650 (1984).
[22] S. Glowacz, H. Hora, J. Badziak, S. Jablonski, Y. Cang, and F. Osman, Laser Part. Beams **24**, 15 (2006).
[23] Y. Cang, F. Osman, H. Hora, J. Zhang, J. Badziak, J. Wolowski, K. Jungwirth, K. Rohlena, and J. Ullschmied, J. Plasma Phys. **71**, 35 (2005).
[24] E. Yazdani, Y. Cang, R. Sadighi-Bonabi, H. Hora, and F. Osman, Laser Part. Beams **27**, 149 (2009); R. Sadighi-Bonabi, H. Hora, Z. Riazi, E. Yazdani, and S. K. Sadighi, *ibid.* **28**, 101 (2010).
[25] H. Haseroth and H. Hora, Laser Part. Beams **14**, 393 (1996).