Laser and Particle Beams (2009), *27*, 149–156. Printed in the USA.
Copyright © 2009 Cambridge University Press 0263-0346/09 $20.00
doi:10.1017/S0263034609000214

Layers from initial Rayleigh density profiles by directed nonlinear force driven plasma blocks for alternative fast ignition

E. YAZDANI,[1] Y. CANG,[2,3] R. SADIGHI-BONABI,[1] H. HORA,[4] AND F. OSMAN[2,5]

[1]Physics Department, Sharif University of Technology, Tehran, Iran
[2]School of Computation and Mathematics, University of Western Sydney, Penrith, Australia
[3]Institute of Physics, Chinese Academy of Sciences, Beijing, China
[4]Department of Theoretical Physics, University of New South Wales, Sydney, Australia
[5]present address: Department of Mathematics, Trinity College, Summer Hill, Australia

(RECEIVED 1 November 2008; ACCEPTED 2 December 2008)

Abstract

Measurement of extremely new phenomena during the interaction of laser pulses with terawatt and higher power and picoseconds with plasmas arrived at drastically different anomalies in contrast to the usual observations if the laser pulses were very clean with a contrast ratio higher than 10^8. This was guaranteed by the suppression of prepulses during less than dozens of ps before the arrival of the main pulse resulting in the suppression of relativistic self-focusing. This anomaly was confirmed in many experimental details, and explained and numerically reproduced as a nonlinear force acceleration of skin layers generating quasi-neutral plasma blocks with ion current densities above 10^{11} A/cm^2. This may support the requirement to produce a fast ignition deuterium tritium fusion at densities not much higher than the solid state by a single shot PW-ps laser pulse. With the aim to achieve separately studied ignition conditions, we are studying numerically how the necessary nonlinear force accelerated plasma blocks may reach the highest possible thickness by using optimized dielectric properties of the irradiated plasma. The use of double Rayleigh initial density profiles results in many wavelength thick low reflectivity directed plasma blocks of modest temperatures. Results of computations with the genuine two-fluid model are presented.

Keywords: Fast igniter; Fusion energy; Laser driven IFE; Dielectric properties of plasmas; Rayleigh profiles; Genuine two-fluid computations

INTRODUCTION

With the aim of generating fusion energy by fast ignition (Tabak *et al.*, 1994), using terawatt (TW) to petawatt (PW) laser power, and picosecond (ps) and shorter duration, a rarely reported anomaly was measured within the broad stream of the research. Instead of the usually emitted very intense and hard X-rays, only very lower intensities and softer X-rays were measured (Zhang *et al.*, 1998), and instead of the usually expected 22 MeV fast Cu ions, only half MeV ions were measured, where the number of the ions did not depend on the laser pulse energy (Badziak *et al.*, 1999). This was clarified (Hora *et al.*, 2002) from the fact that these anomalous measurements were done with exceptionally clean laser pulses, where any prepulse was suppressed by a factor of 10^8 (contrast ratio) up to about 10 ps before the main pulse arrived at the target. Under these conditions, it could be concluded that no relativistic self focusing could have been involved, where the usually generated longer prepulse permitted relativistic self-focusing (Hora *et al.*, 2007) of the laser beams down to a wavelength diameter with extremely high intensity causing very complex relativistic effects (Cowan *et al.*, 1999).

This omission of self-focusing was observed under very special conditions using similar clean laser pulses with very high contrast ratio (suppression of prepulses by a factor of 10^8 or more until dozens of ps before the arrival of the main pulse), where the interaction occurred within the plane geometry of the target only (Sauerbrey, 1996), as a most exceptional case. This all could be explained by the acceleration of the very fast ions as a block from the skin

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

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

layer surface in full agreement with the acceleration by the nonlinear (ponderomotive) force (Hora *et al.*, 2002, 2007). This skin layer acceleration by the nonlinear force (SLANF) was confirmed experimentally from the highly directed space charge neutral plasma blocks with directed current densities above 10^{11} A/cm^2 of ions up to 100 keV (Badziak *et al.*, 2004, 2006).

The use of these extremely intense ion currents for fusion energy generation was mentioned before (Hora, 2003, 2007; Hora *et al.*, 2005; Osman *et al.*, 2004). This is similar to the very high gain laser fusion energy scheme of Nuckolls and Wood (2005), by using very intense 5 MeV electron beams produced by 10 PW/ps laser pulses. These schemes are all special modifications of the fast ignition scheme (Tabak *et al.*, 1994), however, it is a postulate of Dean (2008) to aim at a single laser-plasma interaction process, which may be reached at present only by the here discussed ion option scheme (Ghorannviss *et al.*, 2008, see third and fourth paragraph of Section 1, and see Fig. 1). One problem with the ion beam option is indicated in Hora *et al.* (2007). It consists in the fact that the initially accelerated plasma blocks are rather thin and can be changed into more massive blocks by conically guided motion. Another problem is given by the conditions of extremely high energy flux densities of the directed blocks at interaction with the deuterium tritium fuel (Ghoranneviss *et al.*, 2008; Hora *et al.*, 2008).

The here reported studies are following the earlier noticed numerical results that the thickness of the laser accelerated blocks can be highly increased by dielectric plasma effects, if an appropriate initial plasma density may be produced as given by the theory of Rayleigh density profiles. The motivation for this direction of research was given by earlier one-dimensional one-fluid hydrodynamic computations (Fig. 2), where the dielectric swelling of the laser field was generating plasma blocks of more than 20 vacuum wavelengths thickness (Lawrence, 1978; see Hora, 1991, Section 10.5) by using Rayleigh profiles. After first summarizing properties of these profiles, we report very detailed results about thick, nonlinear force driven (Hora, 1991, Section 8) plasma block generation using the very general genuine two-fluid hydrodynamics (Lalousis & Hora, 1983; Hora *et al.*, 1984; Cang *et al.*, 2005).

ANALYTICAL SOLUTIONS WITH RAYLEIGH PROFILES

One of the fundamental problems of wave propagation in plasmas is the fact that these plasmas are nearly always inhomogeneous. The problems are summarized by Hora (1991, Section 7). This all is related to the solution of the ordinary linear differential equation for the spatial-dependent electric field amplitude *E(x)* (here depending on the spatial coordinate *x*), combined with the spatial dependence of the magnetic field *H(x)* (here also dependent on *x*) by the

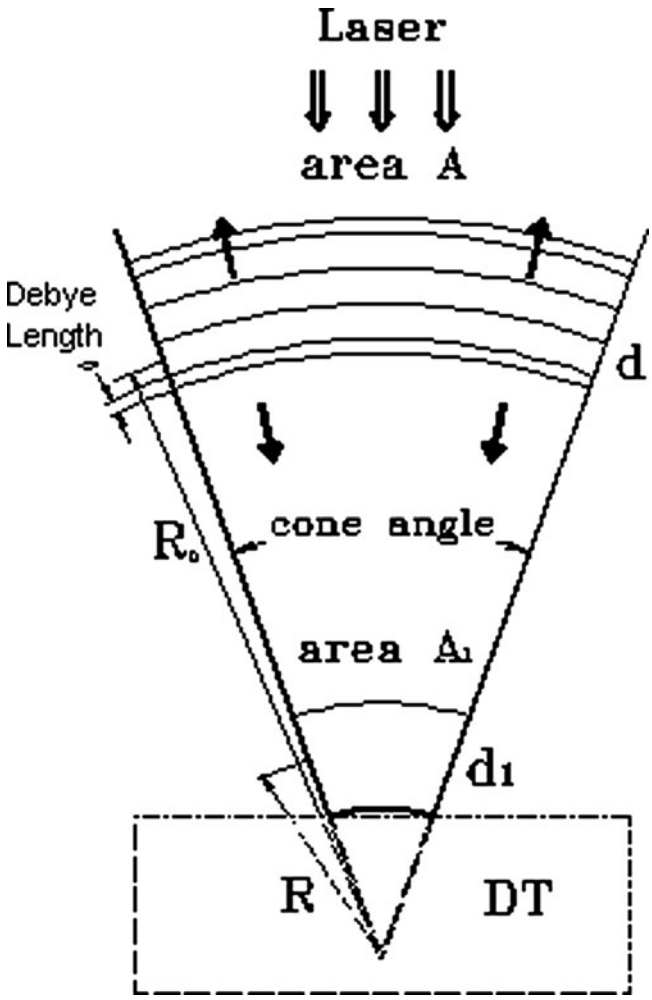


Fig. 1. Schematic description of spherical laser irradiation on a deuterium tritium layer (upper part) to generate a plasma block moving into a cone. The thermal broadening of the block, while having a highly directed 80 keV ion energy for moving into a deuterium tritium target, leads to an isochoric volume of very much larger thickness of the block (Hora *et al.*, 2007).

Maxwell equations,

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

where ω is the radiation 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

$$n(x)^2 = 1 - (\omega/\omega_p)^2/(1 + i\nu/\omega); \qquad \omega_p^2 = 4\pi e^2 n_e(x)/m, \qquad (2)$$

where ω_p is the spatially and temporally varying plasma frequency, ν is the similarly varying electron-ion collision frequency of the plasma, e is the charge, m is the mass, and n_e is the density of the electrons in the plasma. For the analytical discussions in this section, the collision frequency is assumed to be zero (collisionless plasma) in difference to the following numerical hydrodynamic equations with spatially and temporally varying ν and ω_p. The oscillation (Eq. (1)) is trivial if n_e is constant (homogeneous plasma). In this case, the

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

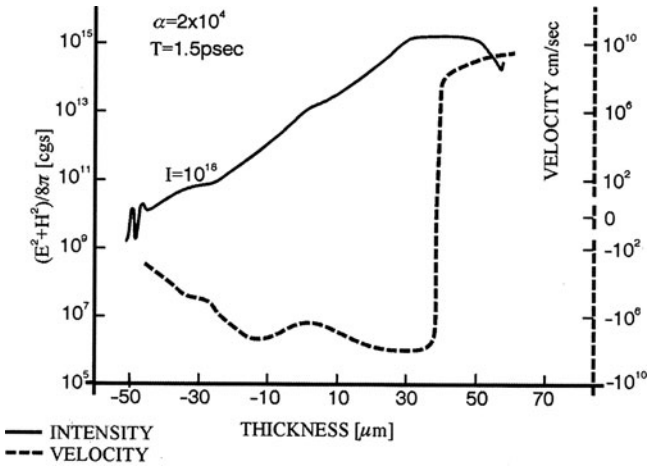


Fig. 2. Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100 eV hot and 100 μm thick bi-Rayleigh profile (see Hora, 1991, Fig. 10.17) with minimum internal reflection. The electromagnetic energy density $(E^2 + H^2)/(8\pi)$ is shown at the time of 1.5 ps after begin of the constant irradiation for comparison with the results of Cang *et al.* (2005).

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) contains the main part of all mathematics of the 19th-century, which means Bessel, Hankel, or Neumann functions, which may be presented by infinite series of orthonormal functions.

For the general case of plasmas with no specific variation of the electron distribution $n_e(x)$, even all these higher functions cannot be used directly. One has, for instance, to use Fourier series of an infinite number of elements containing Bessel etc. functions as later applied in functional analysis. Another way to solve the general wave Eq. (1) is to use the Jordan-Wentzel-Kramers-Brillouin (JWKB) approximation, as was necessary for wave problems in quantum mechanics. A further approximate solution for plasmas uses the approximate presentation of the inhomogeneous optical medium by dividing it into a large number of layers with constant values of n, and solving the problem by multilayer reflection. A paradoxical result was shown numerically (Lawrence & Hora, 1980), where such a multilayer arrangement gave a solution different from the exact one.

In this situation, it was rather unique that Rayleigh (1880) found a solution to the wave (Eq. (1)) for an inhomogeneous medium with a refractive index of the form

$$n = 1/(1 + \alpha x), \tag{3}$$

with constant α. The solution was exactly expressed by elementary functions and amplitude E_0

$$E(x) = (1 + \alpha x)^{1/2} E_0 \exp\{\pm (i/2)[(2\omega/c\alpha)^2 - 1]^{1/2} \ln(1 + \alpha x)\}. \tag{4}$$

With this exact solution, the reflection between a homogeneous and an inhomogeneous Rayleigh medium could be solved precisely (Schlick, 1904), and its was clarified (Hora, 1957) that there exist only two such exact solutions in the inhomogeneous optical medium, one for a wave moving to $+x$ and one for a wave moving to $-x$. There were no internal reflections appearing, as it was suggested within the many-layer approximation. This result with no internal reflection being shown generally for any medium (not only for the Rayleigh case), which was a rather surprise for Osterberg (1958). The exact solutions for a Rayleigh medium for $x > 0$ are shown in Figure 3 (Hora, 1994). The decreasing refractive index in the plasma causes an increase (swelling) of the electric field amplitude, while the Maxwell equations enforce a reduction of the magnetic field amplitude, such that the Poynting vector in the collisionless plasma is constant. The dielectrics cause an increase of the wavelength in the plasma. The value of α causes a phase shift between E and H. This phase shift enforces the reflectivity at the boundary between the vacuum ($x < 0$) and the inhomogeneous Rayleigh medium though the refractive index Eq. (2) is continuous (Schlick, 1904, Hora, 1957).

For the dynamics of the plasma, in the presence of sufficiently high intensity laser beams, the nonlinear (ponderomotive) forces f_{NL} are driving the electron fluid of the plasma, while the ion fluid is then following by attraction due to the electric fields apart from the thermokinetic forces given by the gas-dynamic pressure (excluded in this section, but included in the following computations). The force f_{NL} may be given in the simplified form for one dimension by

$$f_{NL} = -(\partial/\partial x)(E^2 + H^2)/(8\pi) = (n^2 - 1)\nabla E^2/(8\pi). \tag{5}$$

With respect to the result for the Rayleigh profiles (Eq. (4)), the main limitation is that propagating waves are considered to require an oscillating exponential function. This is fulfilled as long as

$$4\omega^2/(c^2\alpha^2) - 1 > 0; \qquad \alpha < 1.1 \times 10^5 \text{cm}^{-1}, \tag{6}$$

where the limit for α is given for neodymium glass lasers. It was evaluated before (Hora, 1957) that propagating waves can have values very close to this limit without causing too high reflectivity at the boundary toward vacuum. In the following, we shall consider mostly cases where $(n^2 - 1) = -n_e/n_{ec}$ is close to unity where n_{ec} is the critical density with $\omega = \omega_p$. Apart from the fast oscillating part in Eq. (4), where the absolute value of the exponential function is equal or less than 1, the ponderomotive action is given, with the Rayleigh refraction index Eq. (3), by

$$\nabla E^2 = E_0(d/dx)/n = \alpha, \tag{7}$$

this is constant, confirming that the whole plasma is then accelerated as an undistorted block. This property of the

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

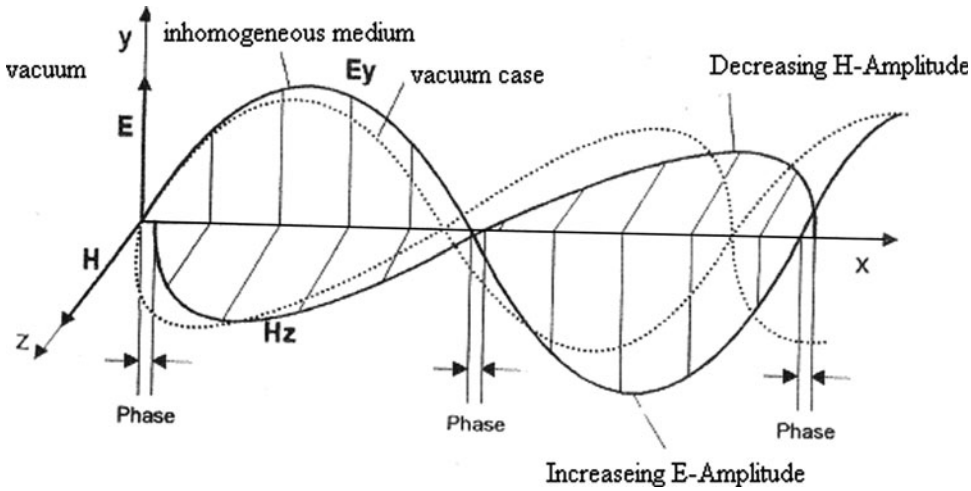


Fig. 3. Exact electromagnetic wave field in a Rayleigh density profile of a collisionless plasma connected with vacuum at $x < 0$ (full line) compared with the vacuum field (dotted line). $x = 0$ coincides with the origin of the coordinate system (Hora, 1994).

Rayleigh profile with respect to the nonlinear (ponderomotive) force is very significant and important to generate uniformly fast moving plasma blocks for applications, and it was immediately seen from the plasma blocks in Figure 2.

COMPUTATION WITH GENUINE TWO-FLUID HYDRODYNAMICS

The generation of the plasma blocks as SLANF is indeed restricted only to the very thin plasma depth of the skin layer. Nevertheless, the dielectric properties are causing an effective increase of the optical wavelength in the plasma above the values of the vacuum. This could be immediately seen when the genuine two-fluid computations were performed for irradiation of plasmas with initial linearly increasing density ramps (Cang *et al.*, 2005). The much thicker skin layers with initial Rayleigh density profiles was shown in the one-fluid computations (Lawrence, 1978) as given in Figure 2. For further illustration, Figure 4 is showing how rather thick compressing blocks of plasmas were seen in the one-fluid computations, where the detailed hydrodynamics including heating, equipartition, and thermal driving of the plasma was producing standing wave components, causing density ripples by the nonlinear force and rather complicated properties at later times, mostly after a few ps of interaction.

For comparison with Figure 4 for the irradiation intensity I of 10^{16} W/cm^2 of the neodymium glass lasers on deuterium plasmas, the interaction of a 300 fs laser pulse with an initially 10 eV hot plasma with an alpha value of 0.959×10^4 cm^{-1}, and an initially 20 μm thick bi-Rayleigh density profile (in contrast to the 100 μm thick profiles considered (Hora, 1991, Fig. 10.17)) was studied. The print of the ion velocity profile for this study is shown in Figure 5. Again a compressing plasma block of about 7.5 vacuum wavelengths thickness is generated.

For the same case, Figure 6 shows the printout of the profiles of the electron velocity in the x-direction (parallel to the laser axis). These correspond to the laser driven Langmuir

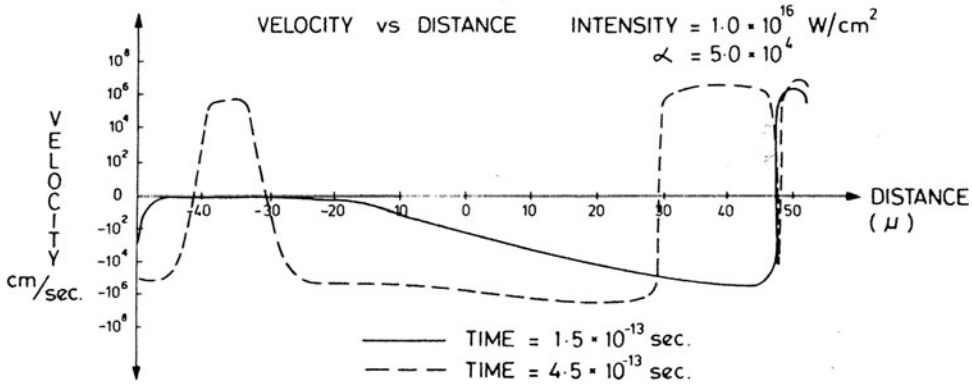


Fig. 4. One fluid computation (Lawrence, 1978) of the velocity of a deuterium plasma of initially 100 μm thickness of an initially bi-Rayleigh density profile with $\alpha = 5 \times 10^4$ cm^{-1} and 100 eV temperature, at 10^{16} W/cm^2 irradiation of neodymium glass laser radiation. The generated plasma block moving against the laser light (to the right hand side) is about 5 wavelength thick at 150 fs irradiation time, and without increasing the velocity to higher values than few 10^6 cm/s, the block gets a thickness of nearly 20 wave length at 450 fs.

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

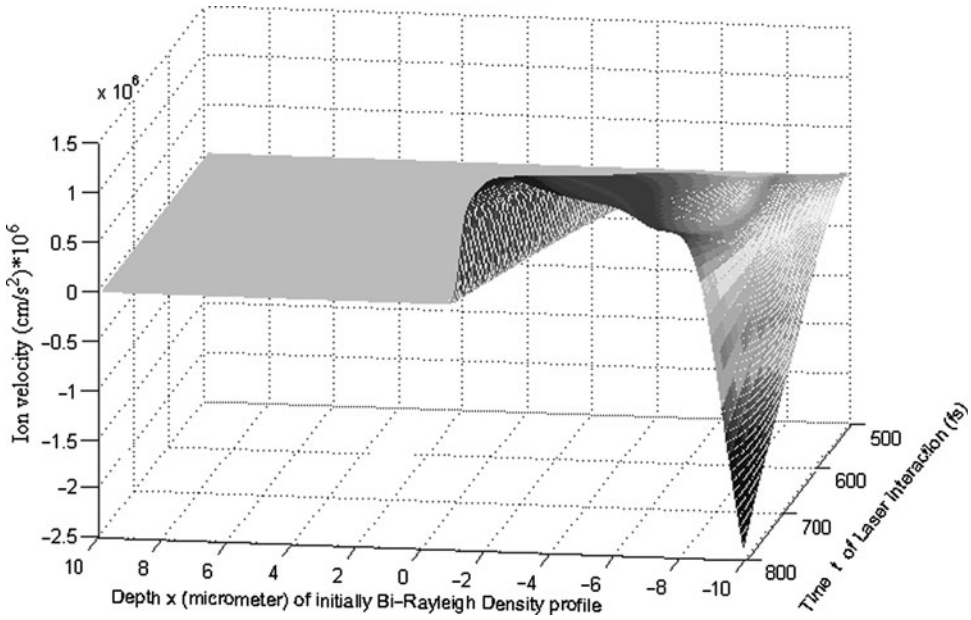


Fig. 5. Ion velocity $v_i(x)$ profiles of a 20 μm initially bi-Rayleigh deuterium plasma layer with $\alpha = 0.959 \times 10^4$ cm^{-1} at an initial temperature of 10 eV depending on time t for a 300 fs laser pulse of 10^{16} W/cm^2 intensity beginning at 500 fs.

oscillations with maximum amplitudes of 2×10^7 cm/s. It is noticed that the maximum quiver velocity under these conditions (perpendicular to the x-direction) is 1.59×10^9 cm/s, confirming the result obtained by many earlier numerical studies (Hora, 1991) that the longitudinal electric field is always smaller by at least a factor of 10 compared with the transversal electric field of the laser.

The printout of the electron velocity profiles depending on time (Fig. 7) is of interest with its wedge-like result. Apart from the oscillating motion against the laser light between -10 and -9 μm, one sees that the wedge develops with a speed of about 1.5×10^9 cm/s, therefore sufficiently below relativistic conditions permitting the quasi-stationary computations of the laser field and of the laser energy density for the nonlinear force in due course for each time step as performed in the code.

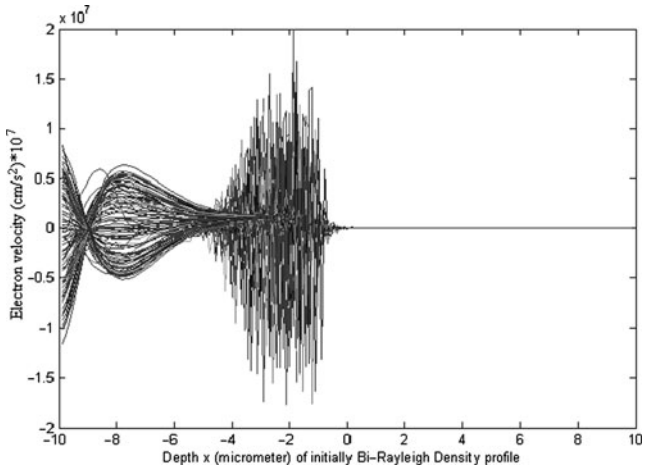


Fig. 6. Overdrawn electron velocity profiles parallel to the laser propagation $v_{ex}(x)$ of the case of Figure 5.

To show how sensibly the computation reacts on very minor changes of the parameters—this may not be related to the final practical problems of the experiments—Figure 8 shows different results, compared with those presented in Figure 5, for the ion velocity profiles, when the initial density profile is increased by 0.1%.

Further the acceleration of the plasma in the compressing block is considered, which was formed during the 300 fs interaction at 3×10^{18} cm/s^2. This is compared with the results obtained by Sauerbrey (1996) (see Hora *et al.*, 2007) for an acceleration of 10^{20} cm/s^2 where KrF laser pulses of the same duration are interacting with fully ionized carbon at 10 times higher laser intensity. The comparison results in an agreement that a dielectric swelling by a factor of 4.33 to 6.5 is included in our case (Fig. 5). This higher swelling than in the case of Sauerbrey (1996) is reasonable, because the effective skin layer has to be enlarged by about the same factor to obtain the nearly 7.5 vacuum-wavelength thick plasma block moving into the target.

For completion, Figure 9 is showing the ion density profile where one can see the generation of the caviton, though the time is very short for the interaction involved.

PLASMA BLOCKS AT VARYING LASER INTENSITY

The detailed case discussed in the preceding section is related to a 100 times lower laser intensity than considered in the case shown in Figure 2. Figure 10 presents the overdrawn

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

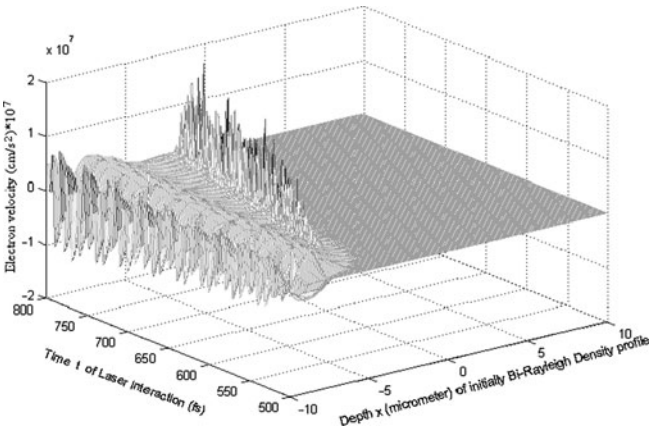


Fig. 7. Time resolved result of Figure 6.

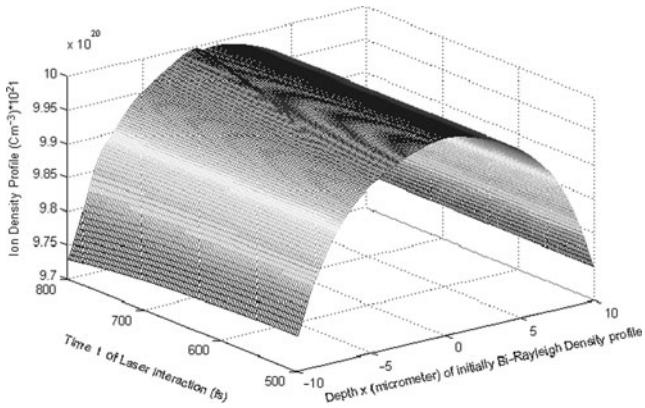


Fig. 9. Ion density profile to the case of Figure 8.

printout of the ion velocity profiles for 300 fs laser pulses, the same α, but an initial temperature of 100 eV at irradiation by a 10^{18} W/cm^2 laser pulse.

It should be realized that the following comparison is very much simplified, since any time dependence of the swelling factor and the difference in the initial temperature is resulting in much more complicated details. Nevertheless, we compare the case of the Figure 5 with an ion velocity in the compressing block of 1.3×10^6 cm/s with that of Figure 10 with a 100 times higher laser pulse intensity. The ion velocity is then 11.4×10^6 cm/s and one may relate these numbers by

$$\varepsilon_i = I^{0.943}, \tag{8}$$

where I is the laser intensity and ε_i the ion energy in the block. This numerically derived result (8) agress exactly with the measured energy of the fast directed ions (Badziak *et al.*, 1999)

These elaborations were performed mainly to demonstrate that rather thick blocks of the "effective skin layer" may be available for the plasma block ignition processes in the area A1 of Figure 1. This is one alternative option of fast ignition for fusion energies at comparably low compression or even solid state density of the deuterium tritium fuel. These advanced results for increased thicknesses were used as parameters for estimating how the block ignition of low compressed or uncompressed solid fusion fuel may eventually be possible (Hora, 2007). We note that the block ignition scheme is just in an early stage of exploration, and by far not comparable with the generation of fusion energy using nanosecond laser pulses (Moses *et al.*, 2006, Bigot, 2006) for spherical compression of fuel. It should not be neglected that a number of phenomena have to be clarified for the block ignition first, e.g., the stopping power mechanism of the alpha particles in the fusion reaction, for instance, whether these are following the Gabor (1952) collective effect (Hora *et al.*, 2008). Significant experimental results (Kerns *et al.*, 1972; Bagge & Hora, 1974; Hoffmann *et al.*, 1990, 2005) drastically indicated that standard binary collision models for the stopping power do not agree with the measurements, and the collective effect is predominant.

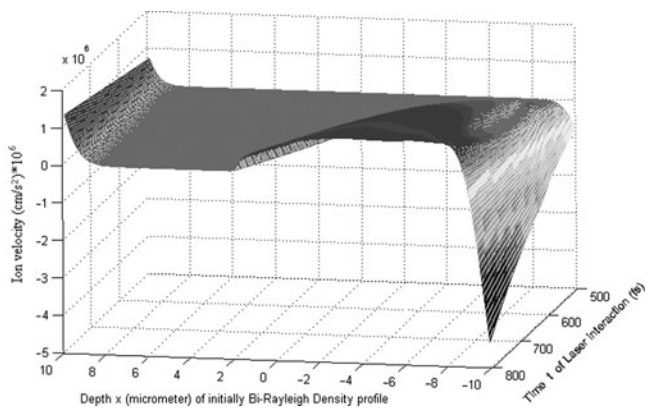


Fig. 8. Ion velocity results for the same case as in Figure 5 but with initial temperature 100 eV and a 0.1% higher initial density.

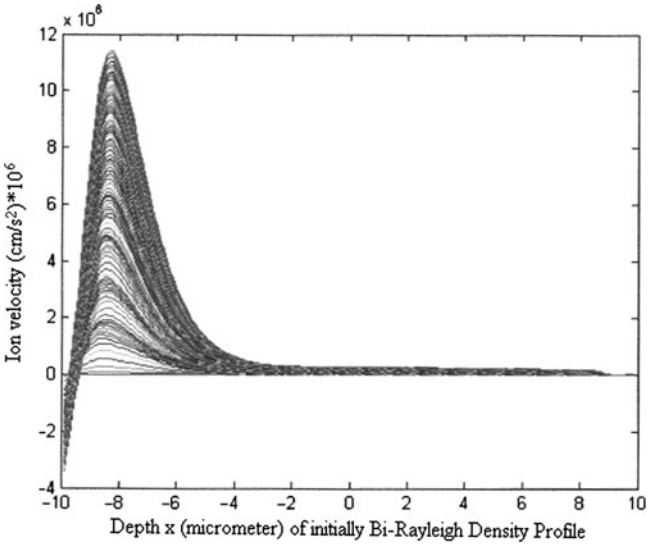


Fig. 10. Overdrawn velocity profiles for the same conditions as in Figure 5, but at initial temperature 100 eV and at intensity 10^{18} W/cm^2 of the laser pulse.

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

CONCLUSIONS

Based on the very detailed genuine two-fluid hydrodynamic plasma code (Lalousis & Hora, 1983; Cang *et al.*, 2005) laser interaction shows how plasma blocks of many vacuum wavelength thickness of plasma in the direction of the laser beam are generated, similar to earlier one-fluid computations (Lawrence, 1978, Hora, 1991) but now with very many more details. The larger thickness is a result by using initial plasma densities with Rayleigh profiles while initial linear ramps of densities could not produce (Cang *et al.*, 2005) such large thicknesses.

REFERENCES

Badziak, J., Glowacz, S., Hora, H., Jablonski, S. & Wolowski, J. (2006). Studies of laser driven generation of fast-density plasma blocks for fast ignition. *Laser Part. Beams* **24**, 249–254.

Badziak, J., Glowacz, S., Jablonski, S., Pahys, P., Wolowski, J. & Hora, H. (2004). Production of ultrahigh ion current densities at skin layer subrelativistic laser-plasma interaction. *Plasma Phys. Control. Fusion* **46**, B541–B555.

Badziak, J., Kozlov, A.A., Makowksi, 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.

Bagge, E. & Hora, H. (1974). Calculation of the reduced penetration depth of relativistic electrons in plasmas for nuclear fusion. *Atomkernenergie* **24**, 143–146.

Bigot, B. (2006). Inertial fusion science in Europe. *J. Phys*. **133**, 3–8.

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

Cowan, T.E., Parry, M.D., Key, M.H., Dittmire, T.R., Hatchett, S.P., Henry, E.A., Mody, J.D., Moran, M.J., Pennington, D.M., Phillips, T.W., Sangster, T.C., Sefcik, J.A., Singh, M.S., Snavely, R.A., Stoyer, M.A., Wilks, S.C, Young, P.E., Takahashi, Y., Dong, B., Fountain, W., Parnell, T., Johnson, J., Hunt, A.W. & Kuhl, T. (1999). High energy electrons, nuclear phenomena and heating in petawatt laser-solid experiments. *Laser Part. Beams* **17**, 773–783.

Dean, S.O. (2008). The rational for and expanding inertial fusion energy program *J. Fusion Energy* **27**, 149–153.

Gabor, D. (1952). Wave theory of plasmas. *Proc. Roy. Soc. London A* **213**, 72–86.

Ghoranneviss, M., Malekynia, B., Hora, H., Miley, G.H. & He, X.-T. (2008). Inhibition factor reduces fast ignition threshold for laser fusion using nonlinear force driven block acceleration. *Laser Part. Beams* **26**, 105–111.

Hoffmann, D.H.H., Blasevic, A., Ni, P., Rosmej, P., Roth, M., Tahir, N.A., Tauschwitz, A., Udera, S., Vanentsov, D., Weyrich, K. & Maron, Y. (2005). Present and future perspectives for high energy density physics with intensive heavy ion and laser beams. *Laser Part. Beams* **23**, 47–54.

Hoffmann, D.H.H., Weyrich, K., Wahl, H., Gardes, D., Bimbot, R. & Fleurier, C. (1990). Energy losses of heavy ions in a plasma target. *Phys. Rev. A* **42**, 2313–2317.

Hora, H. (1957). *Electromagnetic Waves in Media with Continuously Variable Refractive Index*. Jenaer Jahrbuch: Carl Zeiss Jena.

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

Hora, H. (1994). *Elektrodynamik: Felder und Wellen (electrodynamics: fields and waves*. Regensburg, Germany: S. Roderer.

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

Hora, H. (2007). New aspects for fusion energy using inertial confinement. *Laser Part. Beams* **25**, 37–45.

Hora, H. (2009) Laser fusion with nonlinear force driven plasma blocks: thresholds and dielectric effects. *Laser and Particle Beams*, **27** (In press).

Hora, H., Badziak, J., Read, M.N., Li, Yu-Tong, Liang, Tian-Jiao, Liu Hong, Sheng Zheng-Ming, Zhang, Jie, Osman, F., Miley, G.H., Zhang, Weiyan, He, Xianto, Peng, Hanscheng, Glowacz, S., Jablonski, S., Wolowski, J., Skladanowski, Z., Jungwirth, K., Rohlena, K. & Ullschmied, J. (2007). Fast ignition by laser driven particle beams of very high intensity *Phys. Plasmas* **14**, 072701-1–072701-7.

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

Hora, H., Badziak, J., Glowacz, S., Jablonski, S., Skladanowski, Z., Osman, F., Cang, Y., Zhang, J., Miley, G.H., He, X.T., Zhang, W., Rohlena, K., Ullschmied, J. & Jungwirth, K. (2005). Fusion energy from plasma block ignition. *Laser Part. Beams* **23**, 423–432.

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., Malekynia, B., Ghoranneviss, M., Miley, G.H. & He, X. (2008). Twenty times lower ignition threshold for laser driven fusion using collective effects and inhibition factor. *Appl. Phys. Lett*. **93**, 011101-1–011101-3.

Kerns, J.R., Rogers, W.C. & Clark, J.G. (1972). *Bull. Am. Phys. Soc*. **17**, 629.

Lalousis, P. & Hora, H. (1983). First direct electron and ion fluid computation of high electrostatic fields in dense inhomogeneous plasmas with subsequent nonlinear laser interaction *Laser Part. Beams* **1**, 283–304.

Lawreence, V.F. & Hora, H. (1980). A numerical study of wave propagation in inhomogeneous media and the Osterberg problem. *Optik* **55**, 291–302.

Lawrence, V.F. (1978). *Momentum Transfer of Laser Radiation in Inhomogeneous Dielectrics*. Ph.D. Thesis. Sydney, Australia: University of New South Wales.

Moses, E., Miller, G.H. & Kauffman, R.L. (2006). The ICF status and plans in the United States. *J. Phys*. **133**, 9–16.

Nuckolls, J.H. & Wood, L. (2005). Future of inertial fusion energy. In *Edward Teller Lectures*, pp. 13–14. London: Imperial College Press.

Osman, F., Cang, Y., Hora, H., Li-Hua, C., Hong, L., Xiantu, H., Badziak, J., Parys, A.B., Wolowski, J., Woryna, K., Jungwirth, K., Králikova, B., Krása, J., Láska, L., Pfeifer, M., Rohlena,

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press

K., Skála, J., Ullschmied, J. (2004). Skin depth plasma front interaction mechanism with prepulse suppression to avoid relativistic self-focusing for high-gain laser fusion. *Laser & Part. Beams* **22**, 83–87.

Osterberg, H. (1958). Propagation of electromagnetic waves in inhomogeneous media. *J. Opt. Soc. Am*. **48**, 513–519.

Rayleigh, L. (1880). Propagation of waves in inhomogeneous media. *Proc. Royal Soc. London* **11**, 51.

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

Schlick, M. (1904). *About the Reflection of Light in an Inhomogeneous layer*. Ph.D. dissertation. Berlin, Germany: University Berlin.

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

Zhang, P., He, J.T., Chen, D.B., Li, Z.H., Zhang, Y., Wong Lang, Li, Z.H., 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.

https://doi.org/10.1017/S0263034609000214 Published online by Cambridge University Press