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Effect of quantum correction on the acceleration and delayed heating of plasma blocks

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The interaction of laser pulses of picosecond duration and terawatt to petawatt power accelerated for the very fast undistorted plasma blocks for deuterium DD or deuterium tritium fast ignition is investigated. Based on the direct and instant conversion of laser energy into mechanical motion by nonlinear (ponderomotive) forces, any thermal pressure generation is delayed by the collision process. Following the studying of the classical collision frequency, it is found that the quantum modified collision at higher energies results in a correction by about 15% reduction of the delay.

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I. INTRODUCTION

The recent rapid progress in the development of intense short pulse lasers highly motivated applications of these systems for nuclear fusion by using the fast igniter [1]. Propagations of such electromagnetic waves are studied in various plasma conditions [2]. By using these intense lasers, transmutation of hazardous nuclear wastes into the safe and valuable nuclear medicine became possible [3]. Induced heating due to the transport of a fast electron beam generated by an ultrashort pulse laser interaction with solid targets reported, ultraintense fast laser pulses are also used for producing monoenergetic electrons, and hot-electron energy coupling in ultraintense laser-matter interaction is proposed to use for fast ignition [4]. A cone-guided arrangement proposed earlier and recently approved of the energy transport enhancement in this scheme for low-Z targets at laser intensities on targets of up to 2.5×10^{20} W cm^{-2} motivated the use of this model for fast ignition [4] and high current density ions with moderate energies. Ion-acceleration processes have been studied in ultraintense laser plasma interactions for normal incidence irradiation of solid deuterated targets [5]. Experimental confirmation of the skin layer acceleration by the nonlinear force (SLANF) and developing the required theoretical explanations motivated the realistic expectation of the application of using accelerated and very fast plasma blocks above 10^{11} $\mathrm{A/cm^2}$ of ions up to 100 keV for deuterium (DT fast ignition [5]. Following the numerical studies of interaction of picosecond (ps) laser pulses of more than terawatt (TW) power [6], the drastic differences between the thermalization processes and the electrodynamic interaction due to nonlinear (ponderomotive) forces became evident. The same result was confirmed from the measurement of the acceleration of the plasma by using the Doppler effect [7]. The details of these developments and the general nonlinear force theory were summarized before [8]. It is found that the picosecond pulses reached up to the acceleration in the range of 10^{20} $\mathrm{cm/s^2}$, while the acceleration with nanosecond pulses—even with the advanced lasers of the National Ignition Facility (NIF)—arrived only at 10^{15} $\mathrm{cm/s^2}$ as needed by thermal pressure processes for the application of high energy density laboratory astrophysics (HEDLA) [9]. The difference is not only due to the three orders of magnitude shorter interaction time, but also from the fact that the velocity of deuterium plasma arrives at 10^9 cm/s within a picosecond (see Figs. 10.18 a and 10.18 b of Ref. [10]) while the thermal pressure acceleration reaches to about 10^7 cm/s within nanosecond pulses.

The difference can be explained in a direct way by the fact that the nanosecond case is based on the thermal gasdynamic processes that need longer times for the heating process compared with the picosecond case. However, a nonthermalizing direct electrodynamics interaction of the laser radiation with the plasma by the nonlinear ponderomotive force converts the laser energy into mechanical plasma motion instantly. This can be seen from the force density in the one dimension plasma in the direction of x:

$$f = -(\partial/\partial x)nkT/2 - (\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/8\pi. \qquad (1)$$

Here the first term shows the gasdynamic force based on the pressure given by the temperature T with Boltzmann constant k in the plasma with a particle density n and the second term is the nonlinear force f_{NL}, which is determined by the electric field $\mathbf{E}$ and the magnetic field $\mathbf{H}$ of the laser, and where a modification by dielectric properties is essential. Equation (1) is for the one-dimensional plane geometry expression which is reduced from the formulation in three dimensions (see Eqs. (8.87) and (8.88) of Ref. [10]). The nonlinear force acts instantly by the laser field on the (space-charge neutral) electron cloud and the ions follow by electrostatic attraction within a much shorter time than picoseconds. The nonlinear force dominates if the quiver energy in the laser field is larger than the thermal motion of the electrons. In the general treatment, [8] the thermal effects of collisions due to absorption of laser radiation are fully included in the following complete hydrodynamic computations as a marginal effect. The delayed collision heating of the electrons in longer times than the picosecond range modifies the numerical evaluations of plasma blocks [6] needed for the ignition of laser driven fusion of solid state density or modestly compressed fuel [11]. The delayed heating was based on the classical electron-ion

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collision frequency ν_e as it is valid for all cases where the plasma temperature is not too high [6]. For high plasma temperatures, a quantum correction is necessary if the impact parameter for the collisions [12] is smaller than the de Broglie wavelength [13–15]. The following study is the modification of the recent results [6] by including the quantum correction in the investigation of the delayed heating of electrons and consequently the produced ions.

II. THE METHOD

More than half a century ago, Lüst [12] studied a very simple and useful formula from a space-charge-averaged two-fluid plasma model (see Sec. 6.1 of Ref. [10]) that shows the dependence of the complex optical constant $\tilde{n}$, on the laser angular frequency ω, plasma *frequency* ω_p, and the collision frequency ν_{ei}, as the following [12]:

$$\tilde{n}^2 = 1 - \omega_p^2/[\omega^2(1 - i\nu_{ei})/\omega] \tag{2}$$

Application of Eq. (2) was very fruitful in astrophysics and the interaction of laser beams with plasmas [13]. Instead of the classical collision frequency ν_{ei}, the quantum mechanical modification results in Eq. (1), as the following general expression for the electron-ion collisions in Eq. (1) [13,14] is valid:

$$\nu = \left(\pi a_B^2 n_e/4Z^3\right)(3kT/m_e)[(1 + 4T/T^*)^{1/2} - 1]^{-2}, \tag{3}$$

where a_B, n_e, Z, k, T, m_e, and e are Bohr radius, electron density, charge of the collided ion, Boltzmann constant, equilibrium temperature, and the electron mass, respectively, and where $T^* = (4/3k)Z^2 m_e c^2 \alpha^2 = 4.176 \times 10^5 Z^2\,{}^\circ\mathrm{K}$ is given by the electron rest mass, the speed of light c, and the fine structure constant $\alpha_0 = 2\pi e^2/(hc)$ with Planck's constant h in cgs.

The quantum modification of the collision frequency (3) goes back to a formulation by Bethe [15]. This refers to the impact parameter r_0 for the collision of an electron with an ion of charge number Z. Taking into account [14] Bethe's [15] modification of the classical Spitzer and Härm value shows how the collision frequency can be separated into a contribution of small-angle scattering or diffusion-type interaction and other equal contributions of the large-angle scattering [16]. Considering an electron of mass m_e, colliding with a Ze potential of an ion with impact parameter r_0 and velocity υ, a 90° deviation will determine the collision frequency. In the quantum processes it is simply assumed that on the basis of the 90° wave mechanical diffraction [15] model, the momentum $m\upsilon$ produces a product with the conjugated parameter r_0 as $4\pi r_0 m\upsilon = h$ [14]. The point is for calculating the collision frequency, that the mechanical motion of an electron around the ion is limited to 90° hyperbolic motion in fully ionized condition. If the impact parameter has the value of a de Broglie wavelength $\lambda_{\mathrm{dB}} = h/(2mE)^{1/2}$, then instead of the above mentioned hyperbolic motion, wave mechanical scattering has to be used. Following this remark [15], the classical collision frequency has the general value ν as given by Eq. (3) and can be approximated by Taylor expansion with using the classical collision frequency ν_{ei} resulting in Ref. [14]

$$\nu_{ei} = \begin{cases} \dfrac{Z\pi e^4}{3^{3/2} m^{1/2}} \dfrac{n_e}{(kT)^{3/2}} = \nu_{ei}, & T < T^* \\[2ex] \dfrac{Z\pi e^4}{3^{1/2} Z m^{3/2}} \dfrac{n_e}{(kT)^{3/2}} = \nu_{ei} \dfrac{T}{T^*}, & T > T^* \end{cases} \tag{4}$$

III. TWO-FLUID HYDRODYNAMICS COMPUTATION

An advanced and very general hydrodynamic genuine two-fluid code with inclusion of the electric fields (see Sec. 8 of Ref. [10]) was used for the following treatment [5]. In a preceding step the case was treated where the laser pulse strikes an initially increasing linear density ramp [17].

In order to clarify the selection of parameters for initial density profiles, computations were performed mostly with a bi-Rayleigh profile for the initial density including initial temperatures and initial zero macroscopic velocities and the time dependence of the interaction with the laser pulses [5]. Attention was especially given for producing a thick plasma block directed inside the plasma in the laser propagation direction for the conditions described before [4].

More recently, dielectric magnifying of plasma blocks by nonlinear force acceleration with delayed electron heating is reported [6]. In the following, we discuss only deuterium or DT plasmas with $Z = 1$ and find $T^* = 35.9$ eV.

The quantum effect on the collision frequency at high temperatures was measured by the diffusion of plasma across a magnetic field which is determined by the collision frequency (4). In this case, the deuterium plasma temperature of $T = 800$ eV in a stellarator resulted in a 20 times higher diffusion time than that of the classical case [18]. It was noted that $T/T^* = 22$ providing convincing proof of the quantum collision. Another example is the quantum corrected thermal conductivity of electrons, κ_e of the electrons (see Eq. (2.55) of Ref. [10]). With the classical Spitzer value κ_{ei},

$$\begin{aligned} \kappa_e &= \kappa_{ei}\{(T^*/2T)[(1 + 4T/T^*)^{1/2} - 1]\}^2 \\ &= \begin{cases} \kappa_{ei}, & T < T^* \\ \kappa_{ei}(T^*/T), & T > T^*. \end{cases} \end{aligned} \tag{5}$$

The thermal conduction in a tokamak parallel to the magnetic field was measured by Razumova [19] with values rather close to the quantum corrected results (see Fig. 2.6 of Ref. [10]). In contrast to this, the classical thermal conduction was up to 20 times larger than the measurements and the quantum corrected values.

In this work, based on the above mentioned evaluations, the difference of the computations for the cases with classical collision frequency [6] and with the quantum modified collision frequency by using Eqs. (4) and (5) is presented. In this condition, when the critical ion density n_{ec} was chosen to be 10^{21} cm^{-3} during the short interaction time in the range of picoseconds for achieving thick plasma blocks**,** the nonlinear ponderomotive force dominates the thermokinetic forces. For comparison with the preceding case without the quantum correction of the collision [6] we are using the same Rayleigh-density profiles with a continuous refractive index from the vacuum into the inhomogeneous plasma where a kink

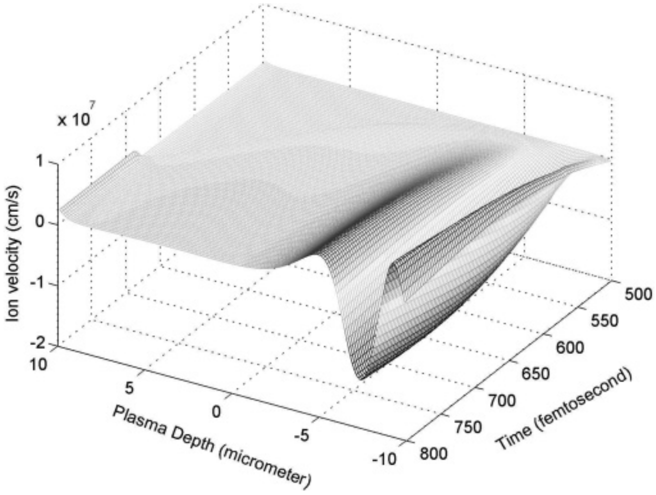

FIG. 1. Ion velocity in an initially bi-Rayleigh (parameter $\alpha = 9.59 \times 10^3\ \mathrm{cm}^{-1}$) deuterium plasma with zero initial ion velocity located between -10 and $+10\ \mu$m. The initial temperature is assumed to be 100 eV at neodymium glass laser intensity of $5 \times 10^{16}\ \mathrm{W/cm^2}$ irradiated from the left-hand side within 300–800 fs. In this figure, the quantum correction in collision frequency is included.

only is needed at the beginning of the plasma (see Sec. 7.3 of Ref. [10]). The kink in both cases is given by a value $\alpha = 9.59 \times 10^3\ \mathrm{cm}^{-1}$ for the neodymium glass laser wavelength $\lambda = 1064$ nm. This results in any reflectivity below 0.1% and determines the depth of the dielectric expanded skin layer above ten vacuum wavelengths. This is sufficiently below the critical value $\alpha_t = 4\lambda/c = 1.18 \times 10^5\ \mathrm{cm}^{-1}$, where the kink—despite the continuous change of the refractive index—results in total reflection at perpendicular incidence what is impossible in the case of a discontinuity of the refractive index. Due to the large difference to α_t compared with the here and before [6] chosen values of α it is confirmed that few percent higher and lower values are changing the following reported results only very marginally. For example, when α changed from $0.959 \times 10^4\ \mathrm{cm}^{-1}$ to $0.979 \times 10^4\ \mathrm{cm}^{-1}$ the electron temperature changed from $9.7 \times 10^{7\circ}$ K to $9.5 \times 10^{7\circ}$ K and this is only about a 2% change.

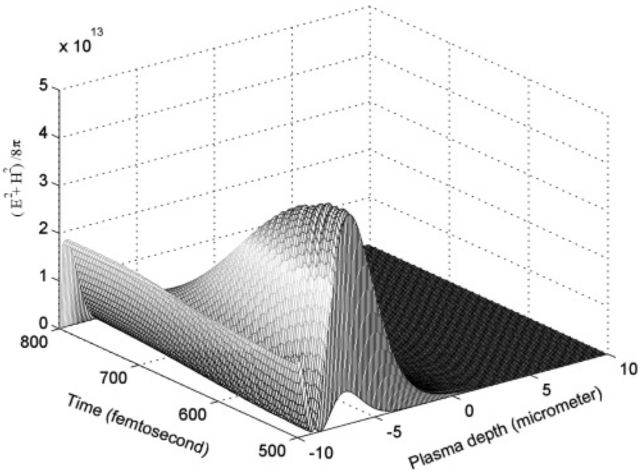

FIG. 2. Electromagnetic field energy density $(\mathbf{E}^2 + \mathbf{H}^2)/8\ \pi$ of the laser in the plasma at 300 fs interaction time for same conditions as in Fig. 1.

IV. RESULTS

When the initial temperature of the plasma was chosen to be 100 eV and laser pulse duration is 300 fs and $5 \times 10^{16}\ \mathrm{W\,cm^{-2}}$ laser intensity with quantum correction for the collision frequency, an ion velocity results as shown in Fig. 1. As one can see, the ion blocks penetrated beyond 16 wavelengths with maximum ion velocity of about 1×10^7cm/s. Figure 2 shows the plot of the penetration of the electromagnetic laser energy density in the plasma with the same conditions as in Fig. 1 with using a 300 fs interaction time.

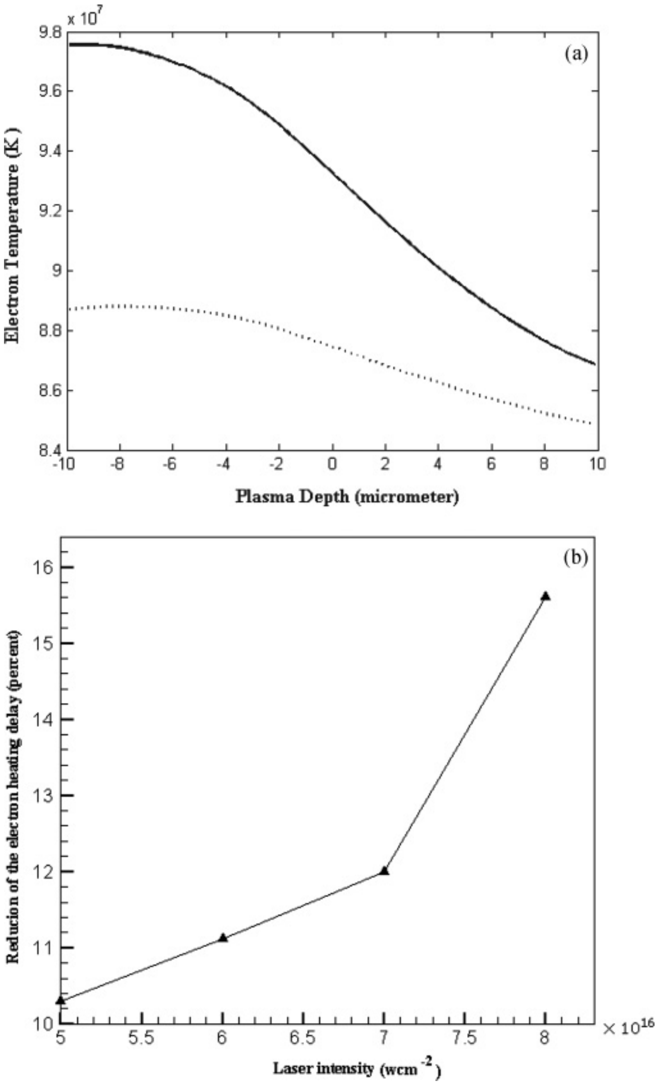

FIG. 3. (a) Electron temperature depending on the plasma depth for two situations is presented: a solid curve for quantum correction in collision frequency and a dotted curve for without quantum correction of collision frequency. (b) This figure denotes the increase of the electron temperature in the laser initial coupling steps by the quantum correction. It increases from 10% to more than 15% when the laser intensity increases from $5 \times 10^{16}\ \mathrm{W\,cm^{-2}}$ to $8 \times 10^{16}\ \mathrm{W\,cm^{-2}}$ in the same condition as (a).

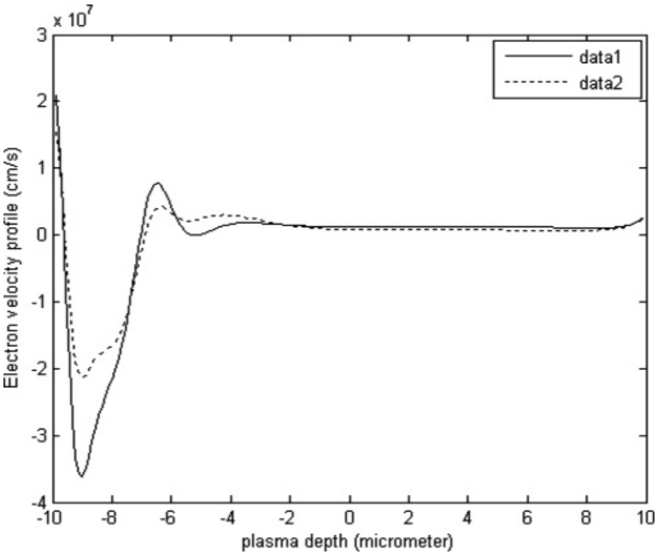

FIG. 4. Electron fluid velocity depending on the plasma depth in cm/s for two states as in Fig. 3(a).

Figure 3(a) shows the comparison of the heating process of the electrons with and without quantum correction in the collision frequency. This is for the initial temperature of electrons at 100 eV which is greater than the critical temperature of 35.9 eV for deuterium atoms($Z = 1$). These curves are obtained for the interaction time of 800 fs. Figure 3(a) shows also how the quantum correction causes about a 10% increase of the electron temperature in the laser initial coupling steps. Figure 3(b) denotes the dependence of the electron temperature on the laser intensity with and without the quantum correction. When laser intensity increases from 5×10^{16} W cm^{-2} to 8×10^{16} W cm^{-2} in the same condition as Fig. 3(a) the electron temperature increases from 10% to more than 15%. It should be realized that the gradient of this increment is faster in the higher intensities. This is a rather considerable modification of the preceding results [6]. Figure 4 is the plot of the profiles of the electron velocity in the x direction (parallel to the laser axis). The solid curve shows the profile of the electron when the quantum correction in the collision frequency is included and the dotted curve is related to an electron velocity without quantum correction. Figure 5 shows the ion temperature depending on the plasma depth for classical collisions (solid curve) and inclusion of the quantum corrections (dotted curve) as in Fig 3(a). The dotted curve denotes that the ion temperature resulted in quantum correction in collision frequency. The difference is rather small. The reasons may be due to the much longer equipartition times. It should be noticed that the ion temperature is not much influenced by the thermal absorption of the electrons and the plasma motion by the ions is determined by the nonlinear force. Figure 6 contains the computations of the ion density profile at 500 fs interaction where the generation of the caviton with an inverted double layer [20] is near the entrance of the laser field with quantum correction in collision frequency. The maximum ion density is below 10^{21} cm^{-3}.

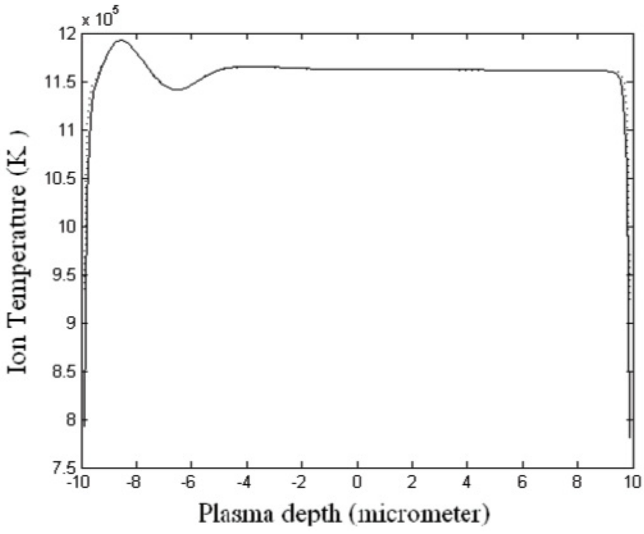

FIG. 5. Ion temperature for the same conditions as in Fig. 1 is shown. One can see the density change in the initial ion movement.

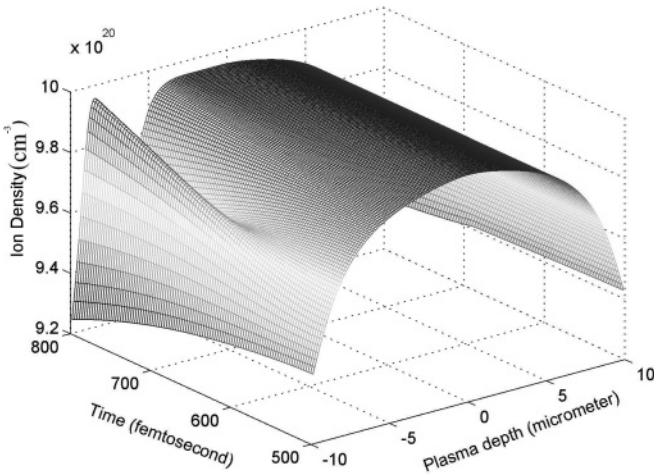

FIG. 6. Plot of the ion density profile for a 500 fs interaction for the same conditions as in Fig. 1 is presented.

V. CONCLUSION AND DICUSSIONS

Based on the quantum mechanical correction of the electron-ion collision frequency at comparably high temperatures in plasma, the preceding calculations [6] of the delay of the electron heating in dielectrically increased plasma blocks was evaluated. It was found that the delay was reduced. However, it is still rather of a value that the application of block ignition to picosecond laser pulses for fusion reactions [5,8,11] needs to be compared with the nonlinear (ponderomotive) force acceleration of plasma blocks without the disturbance by the thermal effects. This disturbance is of influence only at longer laser pulse interaction with plasmas. From the above discussion, one can conclude that due to quantum corrections in the mentioned plasma conditions, the increase of up to 15% electron temperature is tolerable. Although this increase of temperature will result in the reduction of the delay by the same amount, this result is still far from the typical values of block ignition by picosecond laser pulses for fusion. It is a positive result because the typical values of block ignition by picosecond laser pulses for fusion are based on the sufficiently shorter time scales of nonlinear force interaction [5,11,21–24].

This is especially due to the main advantage of working with lasers of shortest available wavelength [4] with suitable pulse duration and intensity. Applying these results to a new computation of the dynamics of the picosecond-pushed ignition process of a fusion flame in solid DT resulted in an evaluation of the of ion densities showing a shock generation of the flame with compressions to four times the initial density in full agreement with the approximative Rankine-Hugoniot theory during the development up to about 100 ps [22]. For later times this mechanism was modified because the approximations of the theory were no longer valid [23].

It should be realized that the plasma hydrodynamic generation of thick plasma blocks due to dielectric effects with a sufficiently short time of the laser interaction in view of thermal effects is a first result only on the way to the side-on ignition of uncompressed or modestly compressed solid density fusion fuel by nonlinear force driven plasma blocks [5,8,11,24].

The plasma block generation [8] includes the possibility of conical geometries where the energetic ions are highly directed and the unavoidably partially heated electrons result in rather low losses by the guiding cones, confirmed also by the preceding [6] and the results which are presented above. The properties for conditions beyond the quasineutral plasma states have been evaluated [25]. These results can be also related to the following advanced ignition schemes of laser fusion.

Shock ignition is introduced [26] with inclusion of modifications of the Lawson criterion [27] following a generalization of earlier results [28] in correspondence with ignition studies and the related considerations [29].

Impact fusion is considered with the recently derived new aspects [30] using two-dimensional conditions [5,8] similar planar geometries [31–33] on the basis of nanostructural clusters [34,35]. Measurements into this direction confirmed a remarkable increase of fusion gains [36]. The relation to the measurement of ultrahigh density clusters [34] with unique properties at laser interaction and generation of MeV energetic particles [35] may be a combination with target experiments containing clusters [36] where the considered new schemes of block ignition, shock ignition, and impact fusion may be combined.

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