

INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA

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Direct ignition of inertial fusion targets by a laser-plasma ion stream

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***Abstract*. This paper outlines the theoretical direct-ignition model of the pre-compressed thermonuclear material of an inertial fusion target under the action of a high-power pulse of light ions from a laser plasma. It is shown that plasma streams with parameters required for the ignition can be obtained from a plane target-generator, located separately from the fusion target upon its fast thermal explosion driven by a high-power laser pulse. This method of direct ignition implies the use of a fusion target whose design provides the supply of the igniting driver energy to the compressed thermonuclear material. This target may be a cylindrical target with partially open ends or a spherical target with one or two conic openings.**

Keywords: *inertial confinement fusion, direct ignition, thermal explosion, light-ion beam.*

1. Introduction

The concept of direct ignition [1, 2] in inertial confinement fusion (ICF) involves a time separation of the compression and heating of the thermonuclear material under target irradiation by two synchronised energy sources (drivers). The compressing driver that acts first is intended for the slow compression of the target material along 'the cold adiabat'. The second (igniting) driver should provide the fast heating of a small part of the compressed thermonuclear fuel in a time not exceeding the period of inertial confinement of the region of primary initiation and ensure the initiation of a self-sustaining wave of thermonuclear combustion. This ignition method allows one to minimise the DT-plasma energy at a level of 20 – 50 kJ upon the attainment of ignition threshold and at a level of 0.3 – 1 MJ upon the initiation of a high-gain combustion wave [1, 2].

The direct ignition offers one more significant advantage, which may prove to be decisive in the ICF problem. The point is that, when attempting to produce the initiation conditions for a thermonuclear combustion wave (a high temperature in the central part of the target, a high density in the surrounding cold material) through hydrodynamic cumulation alone, a serious adverse effect on the formation of the region of primary initiation upon the compression of a spherical target can be exerted by hydrodynamic instabilities, because the deceleration of the peripheral part of the dense thermonuclear material takes place in the low-density central region. The experience gained in ICF research shows that the hydrodynamic instability problem is not easy to solve. Therefore, direct ignition, despite the necessity of using an additional driver, may prove to be not only the cheapest way, but the only possible one.

To accomplish direct ignition, the authors of papers [1, 2] proposed to use ICF targets providing the internal input of the energy of an igniting driver. Such targets may be spherical targets with one or several channels, for instance, conic or cylindrical targets with an opening in one or both end surfaces. To accomplish direct ignition, the authors of paper [3] proposed to form the channel for the input of radiation from an igniting driver directly during irradiation of the spherical target. They proposed to use two laser pulses, one of which produces a channel in the target due to the ponderomotive action and the second one propagates through the channel to deliver energy to the thermonuclear material. This method was called the fast ignition.

The energy transfer to the thermonuclear fuel during ablative compression is accompanied by energy losses in the part of the target being vaporised and the ablator shell. The direct fuel heating by the igniting driver is free from energy losses of this kind, and therefore the compressing driver energy should significantly exceed the igniting driver energy. According to Refs [1, 2], upon the direct ignition of a spherical target, the gain of the order of unity corresponds to the compressing and igniting driver energies of 100 – 200 kJ and 10 – 20 kJ, respectively, while the high gain, for example, 1000 is obtained at energies of 10 MJ and 150 kJ, respectively.

Various combinations of compressing and igniting drivers have been discussed to date. From the viewpoint of energy requirements, the compressing driver can be a short-wavelength laser radiation pulse or a heavy-ion beam. A beam of heavy ions from an accelerator [1, 2], a fast-electron beam produced upon short-wavelength [1 – 3] or long-wavelength [2] laser irradiation of a material, an X-ray radiation pulse [4], and an accelerated material macroparticle [4] have been considered as candidates for the igniting driver.

The conditions for the fast heating of a small mass in the region of primary initiation impose stringent requirements on the igniting driver parameters. This driver should provide a power density delivered to the target of no less than

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$10^{18} - 10^{19}$ W cm^{-2} in a focal spot several tens of microns in diameter for a pulse duration of several tens of picoseconds, with an energy of several tens of kilojoules. From the standpoint of progress in the field of energy concentration of pulsed energy sources, the versions of igniting drivers involving short high-power pulses from solid-state lasers hold the greatest promise. At present, the required pulse duration and radiation intensity have been reached and even exceeded with such lasers [5], though for an energy of only several hundred joules.

Another method of direct ignition using a high-power short laser pulse was proposed in Ref. [6]. It involves the employment of a beam of light megavolt laser-plasma ions produced by laser beam irradiation of a thin plane target-generator of the material of light elements located separately from the thermonuclear target. The light-ion laser-plasma beam may prove to be the best candidate for the igniting driver. The production of a beam of 'accelerator' ions and the stable acceleration of a macroparticle with parameters required for direct ignition in fact involves serious technical difficulties. The application of X-ray radiation requires the generation of high-power nonequilibrium radiation with an intensity of $10^{19} - 10^{20}$ W cm^{-2} and a photon energy of no higher than 500 – 800 eV [6]. The main advantage of an ion igniting driver compared to a fast-electron beam consists in the higher efficiency of energy transfer to the thermonuclear material, which takes place virtually without particle scattering, unlike the fast-electron case.

Below, the theory of direct ignition of ICF targets with an internal energy input under the action of a light megavolt ion beam is developed. The parameters of the laser beam and the target-generator are determined, which are required for the generation of the ion beam to provide the direct ignition of compressed DT and DD fuel.

2. General conditions for direct ignition

Let us assume that a pre-compressed spherical or cylindrical target contains the fuel with the mass M_f and density ρ_p, at temperature $T = 0$. The action of an igniting driver should produce, in a certain part of the fuel having mass M_p, the conditions for the initiation of a thermonuclear combustion wave, which will subsequently extend to the remaining part of the fuel. According to these well-known conditions, the product $\rho_p R_p$ of the density and the dimension of a primary initiation region and the plasma temperature T_p in this region should exceed the certain lower bounds χ_* and T_*:

$$\rho_p R_p \geqslant \chi_* \text{ and } T_p \geqslant T_*, \tag{1}$$

where $\chi = 0.3 - 0.4$ g cm^{-2} and $T_* = 5 - 10$ keV for the DT fuel and $\chi_* = 2 - 4$ g cm^{-2} and $T_* = 50 - 100$ keV for the DD fuel.

The minimal energy E_p and mass M_p (dimension R_p) of the initiation region, which correspond to the lower bounds in (1), are determined by the expressions

$$E_p = A\pi \frac{T_* \chi_*^3}{\rho_p^2}, \tag{2}$$

$$M_p = \pi \frac{\chi_*^3}{\rho_p^2}, \quad R_p = \frac{\chi_*}{\rho_p}, \tag{3}$$

where $A = Ck_B/m_n$ is the specific heat capacity; $C = (z_p + 1)/[\mu_p(\gamma_a - 1)]$; z_p, μ_p and γ_a are the charge and the atomic weight of plasma ions and the adiabatic index of the material in the initiation region, respectively; for DT and DD fuels, the constant $C = 1.2$ and 1.5, respectively; k_B and m_n are the Boltzmann constant and the neutron mass. Hereafter, the temperature, the density, and the parameter ρR are measured in keV, g cm^{-3}, and g cm^{-2}, respectively.

If radiation is absorbed in the plasma without scattering, the absorption length L_d of the igniting driver radiation and the radius R_{opt} of igniting beam should be equal to the dimension of the initiation region (3):

$$L_d = R_{opt} = \frac{\chi_*}{\rho_p}. \tag{4}$$

When absorption of the igniting driver radiation is accompanied by scattering (as, for instance, in the case of a fast electron beam), the absorption length should still be equal to the dimension of initiation region, while the initial beam radius should be smaller than its dimension, i.e., it should be equal to the dimension of the region of initial initiation after scattering.

We present expressions for the optimal parameters of the igniting driver, which are required for the subsequent calculations. These expressions were obtained in Refs [1, 2] assuming that all the igniting driver energy is absorbed in the initiation region and the driver pulse duration is equal to the period of inertial confinement. For an edge ignition, this period is close to the ratio between the region dimension and the sound velocity V_s (in cm s^{-1}):

$$t_p \approx \frac{R_p}{V_s}, \quad V_s = [(\gamma_a - 1)AT_p]^{1/2}$$
$$\approx 3.2 \times 10^7 C^{1/2} (\gamma_a - 1)^{1/2} T_p^{1/2}. \tag{5}$$

The energy (in joules), the duration (in seconds), and the intensity of the optimal igniting pulse (hereafter, in 10^{17} W cm^{-2}) are

$$E_{opt} = E_p \approx 3.1 \times 10^8 C \frac{T_* \chi_*^3}{\rho_p^2}, \tag{6}$$

$$t_{opt} = t_p \approx 3.2 \times 10^{-8} C^{-1/2} (\gamma_a - 1)^{-1/2} \frac{\chi_*}{\rho_p T_*^{1/2}}, \tag{7}$$

$$I_{opt} \approx 3.1 \times 10^{-2} C^{3/2} (\gamma_a - 1)^{1/2} T_*^{3/2} \rho_p, \tag{8}$$

respectively.

For the ignition conditions (1) and a density of compressed thermonuclear material $\rho_p = 300$ g cm^{-3}, the optimal parameters of the igniting pulse, according to expressions (6) – (8), are as follows: duration $t_{opt} \approx 10-$ 20 ps, beam radius $R_{opt} \approx 10 - 20$ μm, energy $E_{opt} \approx 0.5$ -1 kJ, $I_{opt} \approx 10^{18} - 10^{19}$ W cm^{-2} for the DT fuel and t_{opt} $\approx 40 - 70$ ps, $R_{opt} \approx 50 - 100$ μm, $E_{opt} \approx 2 - 3$ MJ, $I_{opt} \approx$ $10^{20} - 10^{21}$ W cm^{-2} for the DD fuel.

3. Direct ignition by a laser-plasma light-ion beam

The main virtue of a high-energy ion beam as the igniting driver is that it provides the efficient energy transfer to the plasma of the initiation region, which occurs virtually without beam scattering. With laser-produced high-energy ions, light ions (or even protons) are preferable from the viewpoint of direct-ignition requirements. This is explained by the fact that, first, lowering the laser-plasma ion charge reduces the bremsstrahlung losses and, second, decreases the charge dispersion of the beam ions, which makes the ion deceleration length defined better and makes easier its matching to the dimension of the initiation region.

One of the conditions for initiation of a thermonuclear combustion wave which underlies relation (1) consists in the approximate equality of the dimension of the ignition region and the paths of charged thermonuclear particles in it whose energies amount to 1 – 3 MeV per nucleon. Clearly, the light ions of the igniting driver which accomplish the initial heating of the fuel in the ignition region should have approximately the same energy – several megaelectronvolts per nucleon.

The generation of fast electrons and ions with energies corresponding to direct ignition is extensively studied in experiments on the irradiation of materials by high-power short laser pulses. In several experiments (see, for instance, Refs [5, 7 – 9]), high-energy ions with energies ranging from several megaelectronvolts to several tens of megaelectronvolts per nucleon were observed. Their generation was accompanied by intense generation of fast electrons with energies ranging from several hundred kiloelectronvolts to several megaelectronvolts.

The experiments were performed employing laser pulses with intensities of $10^{18} - 3 \times 10^{20}$ W cm^{-2} and durations from a fraction of a picosecond to several tens of picoseconds. The laser beam irradiated relatively massive plane targets of plastic, aluminium, and several other materials several hundred microns in thickness, which is comparable to the fast-electron deceleration lengths in these materials. In this case, the ion acceleration at the target edge took place in the self-consistent electric field produced due to the escape of fast electrons from the target. The fraction of laser energy related to the fast ions and their average energy increased with intensity of the laser-pulse intensity.

The maximum fraction of energy carried away by fast ions could be as large as 14 % – 15 % of the laser energy absorbed by the plasma and was recorded in the experiments on the generation of fast protons [5], which were performed for a record pulse intensity of 3×10^{20} W cm^{-2}. The greater part of the energy was accounted for by the protons with energies of 10 – 40 MeV. The light ions of the igniting driver should have a substantially lower energy, which corresponds to lower laser-pulse irradiation intensities and hence to a laser radiation-to-ion beam energy conversion efficiency below 15 %.

From the energy standpoint, a more attractive way of producing the light-ion beam of the igniting driver is the fast thermal explosion of a small mass of material exposed to a high-power short laser pulse. This process can be accomplished by irradiating a thin plane foil made of a light-element material by the laser pulse. In this case, the plasma is heated upon multiple propagations of fast electrons through the foil, which is provided by their reflection in the self-consistent field at the target boundaries. Megavolt ions appear upon the expansion of the heated target material and the conversion of its thermal energy to the energy of directed ion motion.

Generally speaking, upon the thermal explosion of a uniformly heated thin foil (target-generator), the thermal energy of the material is converted to the energy of two oppositely directed hydrodynamic fluxes. However, for a laser radiation intensity above 10^{18} W cm^{-2}, a significant part is played by the ponderomotive light pressure, whose action can lead to a significant violation of the symmetry of material expansion in favour of the plasma stream directed along the laser beam incident on the target-generator.

4. Production of an igniting light-ion beam upon the thermal explosion of a thin foil irradiated by a short laser pulse

Consider the conditions for the interaction of the heating laser pulse with the target-generator, which provide the ion flux with the igniting driver parameters, and determine how close the parameters of the light-ion igniting beam and those of the laser pulse generating this beam can be to the optimal parameters of the igniting pulse.

4.1 Igniting-pulse ion energy

The requirement on the igniting-pulse ion energy follows from the conditions of energy balance in the region of primary initiation and in the target-generator. When the entire laser-pulse energy is absorbed in the target-generator, these conditions are written as

$$n_i E_i \Delta_0 = k_a I_L t_L, \tag{9}$$

$$C\mu_p n_p T_p L_i = k_i \alpha I_L t_L, \tag{10}$$

where E_i and n_i are the ion energy and density, respectively; k_a is the absorption coefficient for laser radiation in the target-generator; k_i is the fraction of laser energy converted to the energy of one-sided ion flux towards the thermonuclear target; $\alpha = (R_L/R_d)^2$ is the factor of ion beam divergence; R_L is the radius of the laser beam which irradiates the target-generator; R_d is the ion-beam radius at the thermonuclear target; Δ_0 is the initial thickness of the target-generator; L_i is the length of the ion absorption region, which is the ion deceleration path (in centimetres) in Coulomb collisions with the electrons of the initiation region [10]:

$$L_i = \frac{3}{8}\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{m_i}{m_e}\right)^{1/2}\frac{E_i^{1/2} T_p^{3/2}}{e^4 z_i^2 z_p n_p \Lambda}$$

$$\approx 4 \times 10^{-3}\left(\frac{E_i}{\mu_i}\right)^{1/2}\left(\frac{\mu_p}{z_p}\right)\left(\frac{\mu_i}{z_i}\right) z_i^{-1}\frac{T_p^{3/2}}{\rho_p}; \tag{11}$$

e and m_e are the electron charge and mass, respectively; z_i, μ_i, m_i are the ion charge, atomic weight, and mass, respectively; Λ is the Coulomb logarithm, which is taken to be equal to 10. Hereafter, E_i is measured in megaelectronvolts.

The laser-radiation absorption coefficient for the high laser-pulse intensity of interest is determined by the resonance absorption coefficient k_e for laser radiation and, generally speaking, by the efficiency k_r of laser-energy transfer to the target-generator as a whole under the action of ponderomotive pressure. The dependence of momentum, acquired by a plane target under light pressure, on the resonance absorption coefficient was obtained in Ref. [11]:

$$\rho_0 \Delta_0 \delta V_i = (2 - k_e)\frac{I_L t_L}{c},$$

where c is the velocity of light and ρ_0 is the initial material density. From this, we obtain the fraction of laser radiation energy transferred to the target via the ponderomotive mechanism:

$$k_r \equiv \frac{\rho_0 \Delta_0 (\delta V_i)^2}{2 I_L t_L} = \frac{1}{2}(2-k_e)^2 \frac{I_L t_L}{c^2 \rho_0 \Delta_0}. \qquad (12)$$

For the pulse intensity $I_L = 10^{19} - 10^{20}$ W cm^{-2} and duration $t_L = 10 - 100$ ps and a thin target with the areal density $\rho_0 \Delta_0 = 10^{-5} - 10^{-4}$ g cm^{-2}, the efficiency of ponderomotive energy transfer may amount to several tens of percent. In the absence of substantial ponderomotive action, the energy of the ion flux from a plane target-generator, which can be employed to heat the initiation region, is equal to half the absorbed laser radiation energy. When the ponderomotive absorption mechanism plays a significant part, more than half the energy absorbed in the target can be converted to the energy of the ion flux directed along the laser beam to the thermonuclear target:

$$k_i = \frac{1}{2}(k_a + k_r), \qquad (13)$$

where $k_a = k_e + k_r$.

The factor of ion beam divergence in the path d from the target-generator to the thermonuclear target is determined by the ratio of the transverse and longitudinal components of the ion velocity and is expressed in terms of the resonance absorption coefficient and the ponderomotive action coefficient as

$$\alpha = \left[1 + \frac{1}{2}\frac{d}{R_L}\left(\frac{k_e}{k_r + k_e}\right)^{1/2}\right]^{-2}. \qquad (14)$$

In the discussion of the divergence problem, consideration must be given to two factors. First, the material of the thermonuclear target under compression which escapes through the surface of the input opening should not arrive at the target-generator prior to the instant of its irradiation by the short laser pulse. Second, the distance d from the input opening to the target-generator should exceed the distance of light-ion beam formation, which should eventually lead to a complete conversion of the thermal energy of the target-generator plasma to the energy of hydrodynamic expansion of the material.

In principle, the first condition can be fulfilled due to specific design of the system consisting of the thermonuclear target and the target-generator, for instance, through the use of a protection diaphragm. Fulfilling the second condition imposes a limitation on the maximum divergence factor. As shown below, the minimal distance required to accomplish the formation of a light-ion flux under the conditions of target heating by fast electrons is $\sim 2.2 R_L$. This means that the maximum divergence factor does not exceed 0.25 when the ponderomotive action does not play a significant part.

The first relation which defines the requirements on the parameters of the target-generator and the heating laser pulse can be easily obtained from energy balance equations:

$$\rho_0 \Delta_0 \frac{E_i}{\mu_i} = 10^{-3} C \chi_* T_* \frac{k_a}{\alpha k_i}. \qquad (15)$$

The condition for matching the length of Coulomb ion deceleration to the dimension of the primary initiation region $L_i = \chi^* / \rho_p$ with the use of expression (12) determines the dependence of the ion energy on the ignition parameters:

$$\frac{E_i}{\mu_i} = 6.25 \times 10^4 z_i^2 \left(\frac{z_i}{\mu_i}\right)^2 \left(\frac{z_p}{\mu_p}\right)^2 \frac{\chi_*^2}{T_*^3}. \qquad (16)$$

We substitute expression (16) in expression (15) to obtain the requirement on the parameter $\rho_0 \Delta_0$ of the target-generator:

$$\rho_0 \Delta_0 = 1.6 \times 10^{-8} C z_i^{-2} \left(\frac{\mu_i}{z_i}\right)^2 \left(\frac{\mu_p}{z_p}\right)^2 \frac{T_*^4}{\chi_*} \frac{k_a}{\alpha k_i}. \qquad (17)$$

The igniting-pulse ion energy decreases, while the parameter $\rho_0 \Delta_0$ of the target-generator corresponding to this energy increases with decreasing the ion charge. For the ignition of the DT fuel, the energy of beryllium ions, for example, should be equal to 27 MeV, and the parameter $\rho_0 \Delta_0$ of the target-generator for $\alpha = 0.25$, $k_a = 0.6$ and $k_i = k_a/2 = 0.3$ should be equal to 7.5×10^{-4} g cm^{-3}. To ignite the DD fuel, these quantities should be 2.3 MeV and 0.3 g cm^{-3}. According to (13), for this beryllium target-generator areal density, the high efficiency of ponderomotive action ($k_e \sim k_r$) corresponds to the laser pulse intensity of 5×10^{19} and 5×10^{23} W cm^{-2} in the cases of the DT and DD fuel, respectively.

4.2 Matching of times

Let us analyse the formation dynamics of the pulse of the laser-plasma ion flux and the matching of the duration of this pulse to the igniting pulse duration. The overall duration of the processes responsible for the formation of the ion-flux pulse, which include the absorption of laser radiation, the fast-electron heating of the thermal electrons of the target-generator and the energy transfer to the plasma ions during the thermal explosion of the target-generator, should not exceed the period of inertial confinement of the material in the initiation region.

For the absorption of the entire laser pulse in the target-generator, the average density of the expanding material by the end of the laser pulse should exceed the critical plasma density ρ_c:

$$\rho_{im} > \rho_c = 1.83 \times 10^{-3} \frac{\mu_i}{z_i \lambda^2}. \qquad (18)$$

Hereafter, λ is expressed in microns and ρ_c in g cm^{-2}. The absorption of laser radiation should take place at the stage of plane expansion of the target, because the plane expansion corresponds to the slowest decrease in the material density, all other factors being the same. This requirement leads to the following limitation on the laser-beam radius R_L:

$$R_L \geqslant \frac{1}{\sqrt{5}} V_i \left(\frac{k_e}{k_e + k_r}\right)^{1/2} t_L. \qquad (19)$$

For a plane expansion, the target density at the pulse termination is

$$\rho_{im} = \frac{\rho_0 \Delta_0}{t_L V_i}, \qquad (20)$$

where, according to (16), the ion velocity (in centimetres per second) is

$$V_i = 3.5 \times 10^{11} z_i \left(\frac{z_i}{\mu_i}\right)\left(\frac{z_p}{\mu_p}\right) \frac{\chi_*}{T_*^{3/2}}. \qquad (21)$$

The fast electron – plasma interaction involves the energy transfer to thermal plasma electrons and the scattering by ions in Coulomb collisions. It was shown in Ref. [12] that the scattering reduces the deceleration path of a fast electron in an infinite plasma by a factor of $(2 + z_i)^{1/2}$. Experiments on the irradiation of plane targets by high-power laser pulses did not reveal a strong electron scattering relative to the direction of laser beam incidence on the target (see, for instance, Refs [5, 7 – 9]). This fact is attributed in the literature to the generation of collimating magnetic fields – spontaneous ones, arising from the existence of crossed plasma temperature and density gradients in the experimental geometry specified above, and intrinsic magnetic fields of the fast-electron current.

Taking this into account, we will perform the subsequent calculations under the assumption that the deceleration of fast electrons in the target-generator occurs within a region with a dimension of the order of the radius of the acting laser beam, but the total deceleration path contains a correction for scattering. By including the scattering factor in the formula for the deceleration path of a relativistic electron from Ref. [13], we obtain the fast-electron deceleration path L_f (in centimetres) and time t_f (in seconds) in the plasma:

$$L_f = \frac{E_f^2}{4\pi e^4 \Lambda(\gamma) n_i z_i (2 + z_i)^{1/2}} \left(1 - \frac{1}{\gamma^2}\right)^2$$

$$\approx 6 \times 10^{-6} \frac{E_f^2}{\rho_i (2 + z_i)^{1/2} \Lambda(\gamma)} \left(\frac{\mu_i}{z_i}\right) \left(1 - \frac{1}{\gamma^2}\right)^2, \qquad (22)$$

$$t_f \approx 4.2 \times 10^{-16} \frac{E_f^{3/2}}{\rho_i \Lambda(\gamma)(2 + z_i)^{1/2}} \left(1 - \frac{1}{\gamma^2}\right)^{3/2} \left(\frac{\mu_i}{z_i}\right), \qquad (23)$$

where E_f is the fast-electron energy (hereafter, in kiloelectronvolts); the Coulomb logarithm $\Lambda(\gamma)$ is a function of the relativistic factor

$$\gamma = \left(1 - \frac{V_e^2}{c^2}\right)^{-1/2}.$$

For a fast-electron energy of 0.5 – 2 MeV, which corresponds to Nd-laser radiation intensities from 10^{19} to 10^{21} W cm^{-2}, the Coulomb logarithm is close to 20.

For subsequent calculations, we will use the well-known scaling for the fast-electron energy [14]

$$E_f = 10^2 \left(I_L \lambda^2\right)^{1/3}. \qquad (24)$$

where I_L and λ are the intensity and the wavelength of laser radiation. By substituting expression (24) in (23), we obtain the deceleration time (in seconds) for a fast electron with velocity a $V_e \sim c$:

$$t_f = 2.1 \times 10^{-13} \frac{\left(I_L \lambda^2\right)^{1/2}}{\rho_i (2 + z_i)^{1/2}} \left(\frac{\mu_i}{z_i}\right). \qquad (25)$$

Taking into account that the fast-electron deceleration time is inversely proportional to the plasma density, we will consider the equality of the laser-pulse duration and the confinement time of the primary initiation region as the criterion for matching the formation time of a target-generator ion pulse to the inertial confinement time. The confinement time should exceed the fast-electron deceleration time at the minimal density ρ_{im} of the expanding target-generator by the end of the laser pulse:

$$t_L = t_d \geqslant t_f(\rho_{im}). \qquad (26)$$

When this condition is fulfilled, the heating of the target-generator can be assumed to terminate approximately at the end of the laser pulse. The time of energy transfer to target-generator ions in this case is the time of target expansion by a distance equal to its thickness for the average density ρ_{im}:

$$t_i \approx \frac{\rho_0 \Delta_0}{\rho_{im} V_i}.$$

Because this time is equal to the time of target expansion from the initial density to the density ρ_{im}, when the matching condition (26) is fulfilled, the time of energy transfer to fast ions also proves to be equal (by the order of magnitude) to the time of inertial confinement of material in the region of primary initiation.

Substituting expression (21) for the ion velocity, expression (17) for the parameter $\rho_0 \Delta_0$, and expression (5) for the inertial confinement time in expression (20), we obtain the target density at the end of the laser pulse:

$$\rho_{im} \approx 1.4 \times 10^{-12} C^{3/2} (\gamma - 1)^{1/2} \frac{T_*^6 \rho_p}{z_i^3 \chi_*^3} \left(\frac{\mu_i}{z_i}\right)^3 \left(\frac{\mu_p}{z_p}\right)^3 \frac{k_a}{k_i \alpha}. \qquad (27)$$

When the conditions for time matching $t_L = t_d = t_{opt}$ and ion-absorption path matching $L_i = \chi_*/\rho_p$ [see (4)] are fulfilled, the parameters of the igniting ion beam and the heating laser pulse are related to those of the optimal ignition pulse as

$$E_d = E_{opt} \alpha^{-1} \left(\frac{R_L}{R_{opt}}\right)^2, \quad t_d = t_{opt}, \quad I_d = I_{opt}, \qquad (28)$$

$$E_L = E_{opt} \alpha^{-1} k_i^{-1} \left(\frac{R_L}{R_{opt}}\right)^2, \quad t_L = t_{opt}, \quad I_L = I_{opt} k_i^{-1} \alpha^{-1}. \qquad (29)$$

By substituting expression (27) sequentially in (18), (26), and (19) and taking into account (29), we obtain that the time matching condition is fulfilled for

$$z_i \left(\frac{z_i}{\mu_i}\right)^{2/3} \leqslant 9.2 \times 10^{-4} C^{1/2} (\gamma_a - 1)^{1/6}$$

$$\times \frac{T_*^2 \rho_p^{1/3} \lambda^{2/3}}{\chi_*} \left(\frac{\mu_p}{z_p}\right) \left(\frac{k_a}{k_i \alpha}\right)^{1/3}, \qquad (30)$$

$$\frac{z_i}{(2 + z_i)^{1/6}} \left(\frac{z_i}{\mu_i}\right)^{2/3} \leqslant 1.06 \times 10^{-2} \left(\frac{C}{\gamma_a - 1}\right)^{1/12}$$

$$\times \frac{T_*^{19/12}}{\chi_*^{2/3} \rho_p^{1/6} \lambda^{1/3}} \left(\frac{\mu_p}{z_p}\right) k_a^{1/3} (k_i \alpha)^{1/6}, \qquad (31)$$

$$R_L \geqslant 5 \times 10^3 z_i \left(\frac{z_i}{\mu_i}\right) \left(\frac{z_p}{\mu_p}\right)$$

$$\times \left(\frac{k_e}{k_e + k_r}\right)^{1/2} \frac{\chi_*^2}{C^{1/2} (\gamma_a - 1)^{1/2} T_*^2 \rho_p}, \qquad (32)$$

where R_L is in centimetres.

These relations allow us to determine the target-generator parameters and characteristics of the igniting ion beam and the heating laser pulse. Conditions (30) and (31), which limit the ion charge of the igniting pulse by neglecting the ponderomotive action of the laser pulse (for $\alpha = 0.5$, $k_a = 0.6, k_i = k_a/2 = 0.3$), give the maximum ion charge $Z_{max} = 3 - 4$ in the case of the DT-fuel ignition and $Z_{max} = 5 - 6$ in the case of the DD-fuel ignition. This means that materials of light elements containing hydrogen and its isotopes (polystyrene, polyethylene, deuterated plastics, DT and DD, etc), beryllium and light beryllium-containing materials, such as beryllium hydride and others, can be employed as the target-generator material. For instance, for a beryllium target-generator and the DT-target ignition, as shown above, the areal target density is 7.5×10^{-4} g cm^{-2} and the thickness of this target should therefore be equal to 4.2 μm.

The condition (32) limiting the radius of the ion igniting beam for a beryllium target gives the minimal beam radius close to the radius of the optimal igniting pulse $R_{min} = 25$ μm in the case of the DT-fuel ignition and 50 μm in the case of the DD-fuel ignition. Furthermore, using relations (28) and (29) in the approximation $R_L \approx R_{opt}$ for the above divergence factor $\alpha = 0.25$ and the fraction $k_i = 0.3$ of laser energy converted to the ion flux to the target, we obtain that the minimal intensity of the igniting beryllium ion beam coincides with the intensity of the optimal igniting pulse: $I_d = I_{opt} \approx 10^{18} - 10^{19}$ W cm^{-2} for the DT-fuel ignition and $I_d = I_{opt} \approx 10^{20} - 10^{21}$ W cm^{-2} for the DD-fuel ignition. However, the minimal beam energy due to its divergence exceeds the energy of the optimal igniting pulse by a factor of four $(E_d = E_{opt}/\alpha){:}\, E_d \approx 2 - 4$ kJ for DT-fuel ignition and 5–10 MJ for DD-fuel ignition.

The heating laser pulse required to generate this igniting ion beam should exceed the ion beam in intensity and energy because of the incomplete conversion of laser energy to the energy of the ion beam incident on the thermonuclear target, and also due to the beam divergence ($E_L = E_d/k_i = E_{opt}/\alpha k_i$, $I_L = I_d/\alpha k_i = I_{opt}/\alpha k_i$)$:E_L \approx 5 - 15$ kJ, $I_L \approx 10^{19}$–10^{20} W cm^{-2} for DT-fuel ignition and $E_L \approx 10 - 30$ MJ, $I_L \approx 10^{21} - 10^{22}$ W cm^{-2} for DD-fuel ignition.

5. Conclusions

Thus, the irradiation of a thin target-generator by a short high-power laser pulse can produce an ion beam with parameters required for the direct ignition of the pre-compressed thermonuclear material of an ICF target. The pulse duration and the focal spot radius of the heating laser pulse are close to the corresponding parameters of the optimal igniting energy pulse. However, because of the ion-beam divergence and the incomplete laser-to-beam energy conversion, the intensity and the energy of the heating laser pulse exceed by an order of magnitude the intensities and the energies of the optimal ignition pulse.

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