Laser and Particle Beams (2005), *23*, 255–260. Printed in the USA.

DOI: 10.1017/S0263034605050305

Thermonuclear gain and parameters of fast ignition ICF-targets*

S. YU. GUS'KOV
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

(RECEIVED 30 November 2004; ACCEPTED 10 December 2004)

Abstract

The requirements of matching shell ICF target parameters, parameters of compressing, and triggering drivers under direct (fast) ignition are developed. Thin shell target, which represents a shell-ablator with a DT-ice layer, frosted on the inner surface of the shell are considered. Design of a target which ensures the energy supply from the triggering driver to the central part of thermonuclear fuel, in both spherical and cylindrical geometry is developed. Spherical target is furnished with one or two conical channels for the injection of the triggering driver radiation. The ends of the cylindrical target are protected by heavy material walls that have the holes of the radius equal to the final radius of compressed fuel. It was found that the parameters of fast ignition spherical and cylindrical targets, which provide high thermonuclear gain of 500–2000 in the range of the compressing driver energy of 1–10 MJ, may be matched with the drivers parameters at low aspect ratios of the targets, 10–20. The operation of spherical targets at the moderate radius convergence ratio of 15–20, may be provided at the triggering driver energy not higher than 30 kJ. The operation of cylindrical target with spin-oriented DT-fuel at radius convergence ratio of 20–25 may be provided at 150–200 kJ of the triggering driver energy.

Keywords: Driver; Ignition; Shell target; Spin-oriented fuel; Thermonuclear gain

1. INTRODUCTION

This work presents a self-similar theory of compression, heating, and burning processes in the inertial fusion spherical, and cylindrical targets under direct (fast) ignition (Basov *et al*., 1991, 1992; Tabak *et al*., 1994; Caruso, 1994). The theory was developed for two-layer thin shell target, which represents a shell-ablator with a DT-ice layer frosted onto the inner surface of the shell. Advanced technologies of production of the high gain targets of such a type were developed (see, for example, Borisenko *et al*., 2003). It is expected that the target design ensures the energy supply from the triggering driver to the central part of thermonuclear fuel of a given mass, and at the same time, allows one to perform a symmetrical radial compression of the target by the compressing driver. In a spherical geometry such a target may be furnished with one or two conical channels for the injection of the triggering driver radiation. A cylindrical target was proposed to be constructed to provide the suppression of the plasma expansion along the direction of target axis. The ends of such a target are protected by the walls which are made of a heavy material and have the holes of the radius equal to the final radius of compressed fuel.

Address correspondence and reprint requests to: S. Yu. Gus'kov, P.N. Lebedev Physical Institute of the Russian Academy of Sciences, 53 Leninski Ave., 119 991 Moscow, Russia. E-mail: guskov@sci.lebedev.ru
*This paper was presented at the 28th ECLIM conference in Rome, Italy.

2. THERMONUCLEAR GAIN OF FAST IGNITION TARGET

For effective burning of fast ignition target, the action of compressing and triggering drivers should result in the following plasma parameters. If we assume that the target with DT fuel reaches, for definiteness sake, a central ignition, the product $\rho_b \times R_b$ of the density and size of all the thermonuclear fuel should be sufficiently high, and, at least, exceed the value of 1 g/cm^2. Then within the region of primary ignition, the conditions should be provided for the initiation of the thermonuclear burning wave, that is, the plasma temperature must exceed 5 keV, and the parameter $\rho_{ig} \times R_{ig}$–0.3 g/cm^2.

The internal energy of cold compressed fuel E_c and primary ignition region E_{ig} are

$$E_C = 3.45 \times 10^5 \times \beta \times M_b \times \rho_b^{2/3},$$
$$E_{ig} = 3.6 \times 10^8 \times (\rho_{ig} \times R_{ig})^3 \rho_b^{-2}, \text{ J} \quad (1)$$

here, M_b and ρ_b are the mass and density of the compressed fuel, β is the degree of degeneration. According to (1), for the effectively burning fast ignition targets with $\rho_b \times R_b > 1$ g/cm^2 and $\rho_b > 100$ g/cm^3, it is correct that $E_c > E_{ig}$. The transfer of the compressing driver energy E_{cd} and the triggering driver energy E_{id} into the plasma intrinsic energy proceeds with a certain efficiency: $E_c = \eta_{cd} E_{cd}$, $E_{ig} = \eta_{id} E_{id}$. The efficiency of transfer of the compressing driver energy is conditioned by the driver radiation absorption efficiency $\eta_{ab} = E_{ab}/E_{id}$ and the efficiency of conversion of the absorbed energy E_{ab} into the intrinsic energy of a thermonuclear plasma. The last value is defined by η_h, the hydrodynamic efficiency of the target compression, and η_t, the efficiency of energy conversion into the intrinsic energy of thermonuclear plasma. $\eta_h = E_h/E_{ab}$ is the ratio between the kinetic energy of the part of the target moving to the centre and the absorbed energy. $\eta_t = E_p/E_h$ is the ratio between the intrinsic energy of the thermonuclear plasma and the kinetic energy of the non-evaporated part of shell.

So, for the compressing driver we have $\eta_d = \eta_{ab}\eta_h\eta_t$. The values of the mentioned efficiencies of energy conversion are as follows (Afanas'ev & Gus'kov, 1993): for the first three harmonics of an Nd-laser of the intensity of 10^{13}–10^{14} W/cm^2: $\eta_{ab} = 0.6$–0.8; $\eta_h = 0.1$–0.4; $\eta_t = 0.5$–0.7. So, $\eta_d = 0.05$–0.15. Following the predictions of Hatchet *et al*. (2000), Gus'kov (2001), and Mulser & Bauer (2004), the efficiency of the triggering driver energy conversion can reach $\eta_{id} = 0.2$–0.3.

So, for the fast ignition targets with high gain we have not only $E_c > E_{ig}$, but $E_{cd} \gg E_{id}$, and, hence, the thermonuclear gain is the ratio between fusion energy E_f and energy E_{cd}

$$G = \frac{q_f \times \varphi \times (1 - v) \times M_b}{E_{cd}}, \quad (2)$$

here $q_f = 3.34 \times 10^{11}$ J/g is the fusion energy released in one gram of DT fuel; ν, the relative fuel mass losses through input holes; φ, the degree of thermonuclear matter burning in the fusion reactions. According to Andreev *et al*. (2002) the expression for φ, generalized to the case of a cylindrical target is

$$\varphi = \frac{0.182}{n^{1/3}} \times (\rho_b \times R_b)^{2/3} \times \left(1 + \frac{M_{ac}}{M_b}\right)^{1/3}$$
$$\text{when } 0.6 < \frac{\rho_b \times R_b}{n^{1/2}} \times \left(1 + \frac{M_{ac}}{M_b}\right)^{1/2} < 3 \text{ g/cm}^2, \quad (3)$$

where for a cylindrical and spherical targets $n = 2,3$, correspondingly, and $M_{ac} = \mu \times M_{ao}$ is the mass of ablator-shell at the moment of maximal compression, M_{a0} is the initial ablator shell mass.

On the base (1), (2) and (3) we get for the gain coefficient

$$G = 2.3 \times 10^2 \times \frac{\eta_{cd}^{11/9} \times \eta_{id}^{5/27}}{n^{1/3} \times \beta^{11/9}} \times E_{cd}^{2/9} \times E_{id}^{5/27}$$
$$\times \left(1 + \frac{M_{ac}}{M_b}\right)^{1/3} \times (1 - \nu) \times \left(\frac{4}{3} \times \frac{R_b}{L}\right)^{2(3-n)/9}, \quad (4)$$

here: L is the length of a cylindrical target; drivers' energy expressed in J here and farther.

One can expect that the design of the input channel in a spherical target may allow to make the fuel mass loses ν insignificant. For cylindrical target when input hole of edge wall has a same radius as compressed fuel radius, R_b, the fuel mass losses may be estimated as

$$\nu \approx \frac{R_b}{2 \times L} \times \left(1 + \frac{M_{ac}}{M_b}\right)^{1/2}.$$

Taking into account the second factor of gain coefficient dependence on cylindrical target length, $G \propto (R_b/L)^{2/9}$, the target length corresponding to the maximal gain equals

$$L_G = \frac{11}{2} \times \left(1 + \frac{M_{ac}}{M_b}\right)^{1/2} \times R_b.$$

The maximal length of a cylindrical target under point-like ignition is defined from the condition that during the confinement time all fuel will be involved by burning wave

$$L_{max} = R_b \times \frac{D_b}{u_c},$$

here D_b is the velocity of a thermonuclear burning wave and u_c is the velocity of target compression toward the centre.

As a result an optimal length of a cylindrical target makes $L_{opt} = min(L_G, L_{max})$. At the low-entropy compression the shell velocity constitutes about $u_c \sim (0.5$–$1)10^7$ cm/s, the velocity of thermonuclear burning wave, $D_b \sim (2$–$3)\ 10^8$ cm/s; the mass ratio M_{ac}/M_b changes within the range of 3–8, so, $L_{max} \approx (20$–$30)\ R_b$, $L_G \approx (10$–$15)\ R_b$. From this follows that under radius convergence ratio $R_0/R_b \approx 20$–40 (R_0 is the initial target radius), the optimal length of a cylindrical fast ignition target makes (0.5–0.3) R_0. One can expect the gain of such a target will be smaller than spherical target one by not more than 2–2.5 times. According to (1), for $\rho_b R_b > 1$ g/cm^2, $\eta_{cd} = 0.1$, $\eta_{cd} = 0.3$ and $E_{id} = 30$–50 kJ the high gain bottom boundary of the compressing driver energy for a spherical target makes 0.5–1 MJ. For a cylindrical target that value in the ratio L/R_b is greater, and for target of optimal length is about 5–10 MJ.

Figure 1 illustrates the dependence of the thermonuclear gain of a spherical fast ignition target on the compressing driver energy at the different triggering driver energies. The

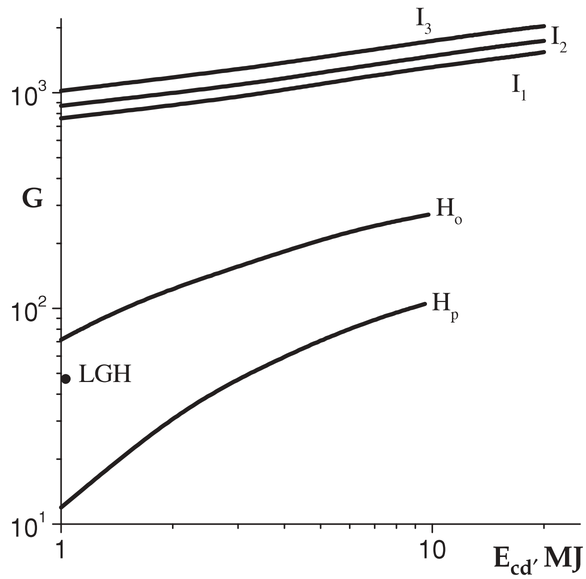

Fig. 1. Thermonuclear gain vs. compressing driver energy. The curves I_1, I_2, I_3 attributed to spherical fast ignition target at triggering driver energies 10, 20 and 50 kJ, respectively; curves H_o and H_p–"optimistic" and "pessimistic" predictions for direct driven shell target; point LGH–"laser greenhouse" target.

efficiencies of drivers energy transfer were taken as $\eta_{cd} = 0.07$ and $\eta_{id} = 0.3$. For comparison, the figure shows also the data on the gain of spherical targets with hydrodynamic "spark ignition," namely, the direct driven thin shell target from (Rozanov *et al.*, 1995) and "laser greenhouse" target (Gus'kov *et al.*, 2003.). The data show that the thermonuclear gain of fast ignition target exceeds by 5–10 times the gain of hydrodynamically ignited targets

3. LOW-ENTROPY COMPRESSION OF A SHELL TARGET

Target compression under the action of a laser pulse with a constant intensity I_{cd} and duration τ_{cd} is described by a model of ablative-driven acceleration of the shell and the model of adiabatic compression (Afanas'ev & Gus'kov, 1993) at the initial entropy introduced in compressed matter by a shock wave initiated by the ablation pressure. The absorption of laser radiation of relatively low intensity, corresponding to low-entropy compression, due to the bremsstrahlung mechanism.

3.1. Ablation acceleration of the shell

The analytical solution for the shell velocity and mass generalized to the case of the target cylindrical geometry is

$$M_a = M_{a0}\left[1 - \psi(\alpha)\,\frac{t}{t_c}\right], \quad u = 2V_a \ln\left[1 - \psi(\alpha)\,\frac{t}{t_c}\right]^{-1}, \qquad (5)$$

where the time of shell motion to the centre (compression time) t_c, final shell velocity u_c expressed through the matter velocity at a critical density region V_a are

$$t_c = \frac{2 \times R_0}{u_c}, \quad u_c \equiv u|_{t=t_c} = 2 \times V_a \times \ln[1 - \psi(\alpha)]^{-1}, \qquad (6)$$

where

$$V_a = \left[\frac{2(\gamma - 1)}{3\gamma - 1} \times \frac{\eta_{ab} \times I_{cd}}{\rho_{cr}}\right]^{1/3},$$

and the function ψ of the dimensionless parameter of the task, the acceleration parameter α, have the form

$$\psi = (\tilde{s} \times \alpha)^{1/2}\left[\left(1 + \frac{\tilde{s} \times \alpha}{16}\right)^{1/2} - \left(\frac{\tilde{s} \times \alpha}{16}\right)^{1/2}\right],$$

$$\text{where } \tilde{s} = \left(\frac{2}{3}\right)^{n-1}$$

and

$$\alpha = \frac{R_0}{\Delta_a} \times \frac{\rho_{cr}}{\rho_a},$$

$$\text{where } \rho_{cr} \approx 1.83 \times 10^{-3}\,\frac{A}{z \times \lambda^2}\ \text{g/cm}^3.$$

Here A and z are the atomic number and the mean ion charge of the evaporated matter, correspondingly; γ, adiabatic exponent; λ, the radiation wavelength of the compressing driver in micrometers; Δ_a and ρ_{a0}, the initial thickness and density of the ablator-shell, correspondingly.

From this one can find the hydrodynamic efficiency

$$\eta = 2 \times \left[\frac{2(\gamma - 1)}{3\gamma - 1}\right] \times \frac{(1 - \psi)}{\psi} \times \ln^2[1 - \psi(\alpha)]^{-1}, \qquad (7)$$

which presents a non-monotonic function of the parameter α, and its maximum for both geometries of the shell makes approximately 0.43. Under the variation of the parameter α, the final velocity and mass of the cylindrical shell changes faster (the velocity grows, and the mass drops) than in the case of a spherical shell. As a consequence, in a cylindrical shell the hydrodynamic efficiency reaches its maximum at $\alpha_m = 1.8$, and shell mass completely evaporates at $\alpha_{ev} = 3$ (the values by 1.5 times smaller than in the case of a spherical shell ($\alpha_m = 2.7$ and $\alpha_{ev} = 4.5$)). The reason is that the surface area of a cylindrical shell decreases with a decrease in the radius more slowly ($S \propto R$), than the surface area of a spherical one ($S \propto R^2$). So, the average surface area of cylindrical shell turns to be greater than for a spherical one, and it ensures more effective acceleration and evaporation.

3.2. Target compression

The state of compressed target is stipulated by the condition of equal pressure in the ablator-shell and fuel, as well as the condition of transfer of the shell kinetic energy into the intrinsic energy of ablator and fuel. The final fuel density ρ_b and energy transfer efficiency η_t are

$$\rho_b = \rho_{b0} \times \left(\frac{\gamma+1}{\gamma-1}\right) \times \left(\frac{\mu \times \eta_t}{y(1+y)} \times \frac{R_0}{\Delta_a} \times \frac{\rho_{a0}}{\rho_{b0}}\right)^{1/(\gamma-1)} \quad (8)$$

$$\eta_t = y \times (1+y)^{1/\gamma} \times \left[y \times (1+y)^{1/\gamma} + \mu \times \left(\frac{\rho_{a0}}{\rho_{b0}}\right)^{1/\gamma}\right]^{-1} \quad (9)$$

and the radius convergence ratio is

$$\frac{R_0}{R_b} = \left(\frac{1}{n \times y} \times \frac{R_0}{\Delta_a} \times \frac{\rho_{bc}}{\rho_{b0}}\right)^{1/n}.$$

In these expressions, the fraction of the non-evaporated shell mass, $\mu = [1 - \psi(\alpha)]$ is defined by the formula (5); $y = \Delta_b/\Delta_a$. Both the values of ρ_b and R_0/R_b increase with the growth of an aspect ratio R_0/Δ_a and the ratio between ablator and fuel masses (the decrease of the y). But that growth of convergence ratio R_0/R_b for the cylindrical target is faster as compared to spherical one. The efficiency η_t slowly decreases with the growth in the ablator and fuel masses ratio. For example, for a plastic shell and DT fuel and under a 4-fold (from 5 to 20) increase in the mass ratio (y decreases from 0.8 to 0.2) the efficiency η_t reduces from 0.6 to 0.4 at $\mu = 0.4$ and from 0.75 to 0.58 at $\mu = 0.2$.

4. THE TARGET AND DRIVERS PARAMETERS AT FAST IGNITION

4.1. The target shell and driver parameters

Matching of these parameters is defined by the following requirements. The laser pulse duration τ_{cd} must be equal to the compression time t_s. The energy balances for triggering and compressing drivers, according to (1) with taking into account of energy transfer efficiencies and expression (8) should be used. For the targets with moderate aspect ratio $R_0/\Delta_a < 50$ (acceleration parameter $\alpha \ll 1$) it is provided (for $\gamma = 5/3$)

$$\frac{M_b}{M_{a0}} = 5 \times 10^{-3} \times \mu \times \eta_t \times \rho_{b0}^{2/3} \times \frac{R_0}{\Delta_a} \times \eta_{id}^{1/3} \times E_{id}^{1/3} \quad (10)$$

$$R_0 \approx 3.8 \times 10^{-3} \left(\frac{2}{27}\right)^{n/6} \frac{\eta_{ab}^{1/3} E_{cd}^{1/3}}{\rho_{a0}^{1/2} \rho_{b0}^{2/9} \beta^{1/3} \lambda^{1/3}} \times \left(\frac{R_0}{\Delta_a}\right)^{1/6} \times \left(1 + \frac{\Delta_b}{\Delta_a}\right)^{1/3} \times \left(\frac{R_0}{L}\right)^{(3-n)/3} \quad (11)$$

$$\tau_{cd} \approx 1.8 \times 10^{-9} \left(\frac{2}{27}\right)^{n/6} \frac{\eta_{ab}^{1/3} E_{cd}^{1/3}}{\rho_{a0}^{1/2} \times \rho_{b0}^{5/9} \times \beta^{5/6} \times \lambda^{1/3}} \times \left(\frac{R_0}{\Delta_a}\right)^{-1/3} \times \left(1 + \frac{\Delta_b}{\Delta_a}\right)^{5/6} \times \left(\frac{R_0}{L}\right)^{(3-n)/3} \quad (12)$$

$$I_{cd} \approx 2.5 \times 10^{13} \left(\frac{27}{8}\right)^{n/2} \frac{(\rho_{a0} \times \beta)^{3/2} \rho_{b0} \times \lambda}{\eta_{ab}} \times \left(1 + \frac{\Delta_b}{\Delta_a}\right)^{-3/2}.$$

And the final velocity of matched shell is

$$u_c = 4.2 \times 10^6 \beta^{1/2} \times \rho^{1/3} \times \left(\frac{R_0}{\Delta_a}\right)^{1/2} \left(1 + \frac{\Delta_b}{\Delta_a}\right)^{-1/2}$$

here the values of R_0, τ_{cd}, I_{cd}, and u_c are measured in cm, s, W/cm^2, and cm/s, respectively.

The radius of matched target grows as the aspect ratio increases and the compressing driver radiation wavelength decreases. Pulse duration of a matched compressing driver increases as the driver energy increases, and the aspect ratio and the wavelength are decreasing. The compressing driver intensity is independent of the aspect ratio and decreases with the wavelength decreasing.

Table 1 collects, calculated by (8)–(12), data of the matched target and the driver's parameters, as well as compressed

Table 1. *Matched target and drivers parameters, as well as compressed thermonuclear plasma parameters and the thermonuclear gain under the compressing driver energy levels of 1 MJ and 10 MJ*

E_{cd}, MJ	τ_{cd}, ns	I_{cd}, 10^{14} W/cm^2	E_{id}, kJ	R_0/Δ_a	R_0, cm	L/R_0	M_a, mg	M_b, g	ρ_b, g/cm^3	$\rho_b R_b$, g/cm^2	R_0/R_b	G
Spherical target												
1	60	0.2	30	17	0.3	—	18	3.2	118	2.1	16.4	650
10	128	0.2	30	17	0.64	—	180	32	118	4.5	16.4	1085
Cylindrical target												
3	225	0.11	90	14	1.02	0.25	112	19	66	1.5	45	600
10	336	0.11	90	14	1.33	0.25	263	45	66	1.95	45	784

thermonuclear plasma parameters and the thermonuclear gain at the compressing driver energy levels of 1 MJ and 10 MJ. The calculations were performed for a plastic shell-ablator ($\rho_a = 1$ g/cm^3) and Nd-laser third harmonic radiation ($\lambda = 0.35$ μm). The only one supposition was made that the absorption efficiency had to be $\eta_{ab} = 0.7$. The targets, which could provide the hydrodynamic efficiency of $\eta_h = 0.2$ were calculated. According to (7), the aspect ratio had to be of 17 for spherical shell and 14 for cylindrical shell, the part of the evaporated mass being of 0.4. The calculated value of the efficiency of the shell kinetic energy transformation into thermonuclear fuel internal energy for all targets was varied in a narrow range of 0.62–0.66.

A cylindrical target, as compared to a spherical target, has an advantages of a more simple and reliable input of triggering driver radiation into the target (Caruso & Strangio, 2001; Basko *et al*, 2002). But at the energy $E_{id} \leq 100$ kJ the cylindrical target is operating at the radius convergence ratio $R_0/R_b \approx 40$–50, which is 2.5–3 times greater that for the spherical target. This circumstance makes the solution of the problem of compression stability for a cylindrical target much more complicated. A decrease in the radius convergence ratio, for a cylindrical target, to the acceptable values of 20–25 may be possible at increasing energy of the triggering driver. The value of such increasing may be significantly reduced by the use of spin-oriented thermonuclear fuel. The use of spin oriented DT-fuel gives a significant profit spatially in fast ignition concept. Indeed, the fusion reaction rate of spin-oriented D and T nuclei is higher in factor 1.5 in comparison with not oriented ones. It leads to decreasing, of the value of ignition parameter $\rho_{ig}R_{ig}$, approximately, in the same factor. Since, according (1) $E_{ig} \times \rho_b^2 \propto (\rho_{ig}R_{ig})^3$ the decreasing factors for triggering driver energy and fuel density can be high enough, respectively, 3.5, and 2. So, the use of spin oriented DT-fuel gives a possibility to decrease within an wide enough range a triggering driver energy or fuel density or both of them (probably, in a different degree). In particular, the calculations show that the fast ignition cylindrical target with spin-oriented DT-fuel may provide the thermonuclear gain of 500–1000 at the radius convergence ratio of 20–25 and the triggering driver energy 150–200 kJ.

4.2. The input channel and edge wall parameters

The functionality of the spherical target input channel consists in guaranteeing the delivery of the triggering driver radiation to the compressed fuel. The channel wall should prevent the propagation of the matter flows into the channel volume under the pressure of the compressed target. The edge walls of cylindrical target must suppress the shell plasma expansion along the direction of target axis.

An important question is the limiting position of the channel apex inside the spherical target. In order to provide central triggering, it seems to be promising to place the channel apex as close to the target centre as possible. However, at the stage of target compression, the part of the channel located on the target centre closer than the compressed fuel boundary, should experience pressure of the matter with a density of several hundreds g/cm^3. Such pressures can be suppressed during the time of inertial confinement only by the channel wall with the thickness comparable to the initial radius of the target. So, it seems to be very difficult to locate the end part of the channel in the area of the thermonuclear matter location. Thus, the most practical way to solve this problem is to reduce the location of the channel apex by the final radius of thermonuclear matter, and for all the triggering drivers this assumes, beside the ion beam, the edge initiation of the thermonuclear burning wave. In this case, the design of the channel must ensure the impediment of the matter expansion into the channel at the stage of the shell acceleration. The shock wave velocity in the channel wall is expressed through the shell velocity in the following form

$$D_w \approx \left[\frac{3 \times (\gamma_w + 1)}{16 \times \gamma_a}\right]^{1/2} \left(\frac{\Delta_{a0}}{R_0} \times \frac{\rho_{a0}}{\rho_{w0}}\right)^{1/2} \times u_c, \qquad (13)$$

here ρ_{w0} and γ_w are respectively, the density and the adiabatic exponent of the channel wall matter.

From this the minimal thickness of the channel wall ($\Delta_w = D_w \times \tau_c$) and the energy losses in the channel with relation to the energy of the accelerated shell we get

$$\Delta_w \approx \left[\frac{3(\gamma_w + 1)}{4 \times \gamma_a}\right]^{1/2} \left(\frac{R_0}{\Delta_{a0}} \times \frac{\rho_{a0}}{\rho_{w0}}\right)^{1/2} \times \Delta_{a0}, \qquad (14)$$

$$\chi \approx \frac{3}{16\mu}\left[\frac{3(\gamma_w + 1)}{\gamma_a^3}\right]^{1/2} \left(\frac{\Delta_{a0}}{R_0} \times \frac{\rho_{a0}}{\rho_{w0}}\right)^{1/2} \sin\frac{\theta}{2}, \qquad (15)$$

here θ is the cone angle and $\sin\theta/2 \approx \Delta_w/\Delta_a + R_b$. Calculations show that θ lies in the range of 60–80 degrees.

At the limitation of the thermonuclear mass loss by the value of (5–10) % such a design of the channel provides the possibility to have the radius of apex hole equal to 2–3 of the triggering beam radius. The formulas (13) and (14) with the coefficient accuracy up to 1 is just for the edge walls of the cylindrical target. As far as the energy losses in the edge walls are concerned, they are given by expression (15) at $\sin\theta/2 = 1$, multiplied by factor of R_0/L. The smaller is the ratio between the densities of the ablator shell and the channel wall, the smaller are the wall thickness and the energy losses. When the wall density essentially exceeds the shell density, for example, by 20, then for the shell with an aspect ratio of 15–20 wall thickness is close to the target shell thickness, 100–300 μm. The energy losses in spherical target channel are 3–5% of shell energy. In cylindrical target with optimal length the energy losses in edge walls is 10–20 % and the mass losses through the holes with radius equal to compressed fuel radius is, approximately, 18%.

5. CONCLUSION

The parameters of fast ignition spherical and cylindrical targets which provide high gain of 500–2000 in the range of compressing driver energy 1–10 MJ may be matched with drivers parameters at low shell aspect ratios, 10–20. Pulse duration and intensity of compressing driver should vary within the ranges of (50–350) ns and (1–2) 10^{13} W/cm^2.

The operation of spherical targets at the moderate radius convergence ratio of 15–20, may be provided at the triggering driver energy not higher than 30 kJ. The cylindrical target operation at the moderate radius convergence ratio would require significantly higher energy of the triggering driver. That energy may be reduced by use a spin-oriented DT-fuel. The operation of cylindrical target with spin-oriented DT-fuel at convergence ratio of 20–25 may be provided at 150–200 kJ of triggering driver energy.

ACKNOWLEDGMENTS

The work was supported by Project # B-0049 of "Basic Optics and Spectroscopy" Educational-Scientific Center and ISTC Project #2155.

REFERENCES

Afanas'ev, Yu.V. & Gus'kov, S.Yu. (1993). Energy transfer to the plasma in laser target. In *Nuclear Fusion by Inertial Confinement* (Velarde, G., Ed.), pp. 99–118. Ann Arbor: CRC Press.

Andreev, A.A., Gus'kov, S.Yu, Il'in D.V, Levkovskii, A.A., Rozanov, V.B. & Sherman, V.E. (2002). On the possibility of target plasma ignition under the conditions of inertial nuclear fusion. *JETP* **96**, 695–703.

Basko, M.M., Churazov, M.D. & Aksenov, A.G. (2002). Prospects of heavy ion fusion in cylindrical geometry. *Laser Part. Beams* **20**, 411–414.

Basov, N.G., Gus'kov, S.Yu. & Feoktistov, L.P. (1991). ICF targets with direct heating of the ignitor. *Proc. 21st European Conference on Laser Interaction with Matter*, Warsaw, Poland, 189–191.

Basov, N.G, Gus'kov, S.Yu. & Feoktistov, L.P. (1992). Thermonuclear gain of ICF targets with direct heating of the ignitor. *J. Soviet Laser Res.* **13**, 396–399.

Borisenko, N.G., Akunets, A.A., Bushuev, V.S., Dorogotovtsev, V.M. & Merkuliev, Yu.A. (2003). Motivation and fabrication methods for inertial confinement fusion and inertial fusion energy targets. *Laser Part. Beams* **21**, 505–509.

Caruso, A. (1995). Gain of laser compressed DT-fuel ignited by injected triggers. *Proc. of I.A.E.A. Technical Committee Meeting on Drivers for Inertial Confinement Fusion*, pp. 325–339. Paris, France.

Caruso, A. & Strangio, C. (2001). Studies on nonconventional high-gain target design for ICF. *Laser Part. Beams* **19**, 295–308.

Gus'kov, S.Yu. (2001). Direct ignition of inertial fusion targets by a laser-plasma ion stream. *Quantum Electronics* **31**, 885–890.

Gus'kov, S.Yu., Demchenko, N.N., Rozanov, V.B., Stepanov R.V., Zmitrenko, N.V., Caruso, A. & Strangio, C. (2003). Symmetric compression of "laser greenhouse targets" by a few laser beams. *Quantum Electronics* **33**, 95–104.

Hatchett, S.P., Brown, C.G., Cowan, Th.E., Henry, E.A., Johnson, J.S., Key, M.H., Koch, J.A., Langdon, A.B., Lasinski, B.F., Lee, R.W., Mackinnon, A.J., Pennington, D.M., Perry, M.D., Phillips, Th.W., Roth, M., Sangster, T.C., Singh, M.S., Snavely, R.A., Stoyer, M.A., Wilks, S.C. & Yasuike, K. (2000). Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets. *Phys. Plasmas* **7**, 2076–2082.

Mulser, P. & Bauer, D. (2004). Fast ignition of fusion pellets with superintense lasers: Concepts, problems and prospectives. *Laser Part. Beams* **22**, 5–12.

Rozanov, V.B., Verdon, C.P., Decroisette, M., Gus'kov, S.Yu., Lindl, J., Nakai, S., Nishihara, M. & Velarde, G. (1995). Inertial confinement target physics. In *Energy from Inertial Fusion* (Hogan, W., Ed.), pp. 1–64. Vienna: INEA

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