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On the problem of acceleration of fast ignition thermonuclear targets with two cones

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The problems of acceleration of fast ignition thermonuclear targets with two cones for their high-precision injection into region near the center of the reactor chamber are considered and the possibility of solution of these problems is shown. A brief review of discussed variants of such targets and of their main advantages, related to ignition of microexplosion and simplicity of providing preservation of targets workability during their flight in the reactor chamber, is presented. Fast ignition by microexplosion of two-sided cone target and the method to estimate acceptable speed of stabilizing rotation of thermonuclear target are proposed.

Keywords: controlled thermonuclear fusion, inertial confinement, fast ignition, two-sided cone targets, spin stabilization of flight.

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Introduction

Most thermonuclear fusion projects using inertial confinement to generate power consider power plants with a single reactor chamber, where microexplosions are initiated at frequency of $f_m \approx 0.1-30$ Hz with energy release of $Y_m \approx 40$ MJ-20 GJ (see, for example, [1–9]). In power plants with f_m of several Hz or higher, fusion targets will be delivered to the reactor chamber and irradiated in free flight by laser radiation or/and ion beams [1–3,9–21]. This will require accelerating the targets to a velocity of $v_t \approx 50-1000$ m/s with ensuring their workability and hitting the irradiation region near the center of the reactor chamber [1,2,9–21]. In this paper, problems associated with such acceleration of fast ignition targets with two cones and possible solutions to these problems are discussed.

1. Concept of fast ignition and some variants of fast ignition targets with two cones

Today the term „fast ignition" is commonly used to describe all scenarios involving two main stages: compression of fuel to high density without significant heating, and heating a large enough area of high-density fuel to ignition temperature T_{ig} with any additional energy source, but without using a focused shock wave (it was originally introduced to describe one of scenarios of such type [22]). Focused shock wave heating [23–26] scenarios are now called „convergent shock wave ignition" or „focused shock wave ignition " [25,26] in Russian; the English literature uses the term „shock ignition" [24]. Fast ignition with strong additional compression of some fuel regions by heating other regions [27–31] has been considered. Such scenarios with heating of compressed regions to T_{ig} [30] can be considered as a combination of fast ignition with convergent shock wave ignition. Fast ignition is interesting because it imposes relatively low requirements to energy delivered to a target to initiate a microexplosion and to fuel compression symmetry necessary to initiate a fixed Y_m microexplosion (see, for example, [3,22,28,32–34]).

Heating the compressed fuel through a cone has been proposed in paper [32]. Some expected advantages of targets with a cone over targets without a cone in terms of microexplosion initiation efficiency in situations where approximately the same scenarios can be realized with and without a cone are discussed in [28,29,34–37] and further. A target with two cones has been proposed in paper [38]. Earlier paper [33] proposed a target with two cone holes. The functions of the cones in the same target may be the same or differ.

It is possible for the same cones to be used to heat different regions of the same clot of compressed fuel [31,38–40]. Ignition in any one of them should be possible regardless of the fact of its achievement in the other one (in other words, the successful formation of a „hot spot" in any of the heated regions should be possible regardless of the success of its formation in the other one). This option is of interest as a tool to achieve high average fuel combustion efficiency and ensuring power plant reliability [31,39,40].

Development of two „hot spots" in a single clot of compressed fuel has been discussed, both using the same cones [31,38–40] and without them [41–44]. One advantage

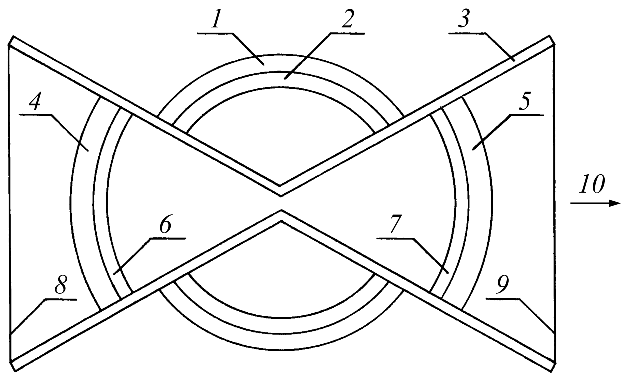

Figure 1. Fast ignition target, of direct compression, for a scenario with formation of „hot spot" in a clot of main compressed fuel by microexplosion of a two-sided cone target: *1* — main fuel ablator, *2* — main fuel, *3* — wall of a two-sided cone target, *4, 5* — ablators of a two-sided cone target, *6, 7* — fuel of a two-sided cone target, *8, 9* — protective membranes, *10* — target flight direction.

of targets with cones relates to the possibility of creating ring-shaped „hot spots" when fuel is heated by laser-accelerated ions [37], which is interesting primarily as a method to minimize the energy required to form a „hot spot" [27]. In addition, development of two ring-shaped „hot spots" can lead to generation of a convergent shock wave resulting in a third „hot spot", which, in turn, leads to high fuel combustion efficiency [31]. Feeding energy to a single clot of compressed fuel from two opposite sides without or with cones can also serve to create a single „hot spot" [34,43,44].

Fig. 1 shows the main parts of a fast ignition, direct compression target for a scenario involving the formation of a „hot spot" in a clot of main compressed fuel by a two-sided cone target microexplosion. This scenario is analogous to the one proposed in paper [36] with formation of a „hot spot" in the main compressed fuel clot by a cone target microexplosion (see also [34,45–48]). Compressing the region near the top of a cone target [34,36] or the middle of a two-sided cone target with the main compressed fuel will contribute to the efficient initiation of microexplosions of these targets. This will likely enable formation of „hot spots" by laser pulses with durations close to that of the pulses compressing the main fuel [34,36].

A target with two cones with fundamentally different functions has been proposed in paper [29]. One of the cones serves directly to form a „hot spot", and the second one — to release gas and/or low-density plasma from the central region of the fuel capsule during its compression and thereby to improve compression [29]. A similar process can also be implemented with a „double-walled cone", the main function of which is to form a „hot spot" (gas and/or plasma will escape through the gap between the walls) [16], two such cones and without using special measures [28,32,41].

2. Linear acceleration and rotational stabilization of fast ignition targets with two cones

2.1. Targets without shell

Most papers on use of fusion microexplosions for power generation consider targets with fuel in the form of deuterium tritium ice. Flight of a target in a reactor chamber must occur without its overheating [2,4,6,10,11,14–16,40,49–52]. A fuel capsule of an indirect initiation and fast ignition, indirect compression target will be isolated from external effects by a shell confining X-ray radiation [10,11] and other structural elements of the target; similar isolation will also be realized in „laser greenhouse" [3,34,53] type targets and fast ignition targets with such fuel compression. Therefore, for such targets, the above requirement will be met either automatically, i.e., without using any special measures, or by relatively simple measures, in particular, by coating the outer surface of the target with frozen xenon (see, for example, [14]). Here we consider a situation where the inner surface of the reactor chamber is protected with xenon [6,7,14–16].

It is possible that preservation of fast ignition, direct compression targets with one or two cones during their flight in reactor chambers of some power plants will be done almost automatically, with an external ablator coating that reflects infrared and visible radiation [50,52], and if necessary optimize geometric parameters of the cones [14]. When the longitudinal axis of such a target coincides with the direction of its flight, the front cone of the target with two cones (fig. 1 and $2, b$) or the cone of a target with a single cone in front of the fuel capsule will serve as a „wake shield" significantly reducing heating of fuel capsule by xenon atoms (the base of this cone must be closed) [14]. Some contribution to reducing the heating of the fuel capsule of the target with two cones will also be made by the rear cone. If necessary, a frozen xenon coating applied to the fuel capsule and/or cone(s) [14] may be used. Hereinafter, to simplify the terminology, the term „fuel capsule" is also used to describe the capsule with the main fuel of the target shown in fig. 1 and its counterparts with one or two cone targets.

A variant of a sabot for accelerating a fast ignition, direct compression target consisting only of a fuel capsule and cones is shown in fig. 2. Effect of the contact surfaces of the sabot parts on the fuel capsule and both cones during linear acceleration of such a target, i.e. when it is accelerated to a velocity v_t, will cause the stresses occurring in the deuterium tritium ice during this process to be similar to those occurring in linear acceleration of direct initiation targets without a cone and fast ignition targets without a cone or with one cone accelerated in respective sabots with the same linear acceleration value a_l (see, for example, [10,11,14,16,20,21]). Separation of sabot parts from the target by springs or gas pressure, also used for its linear acceleration, or centrifugal force associated

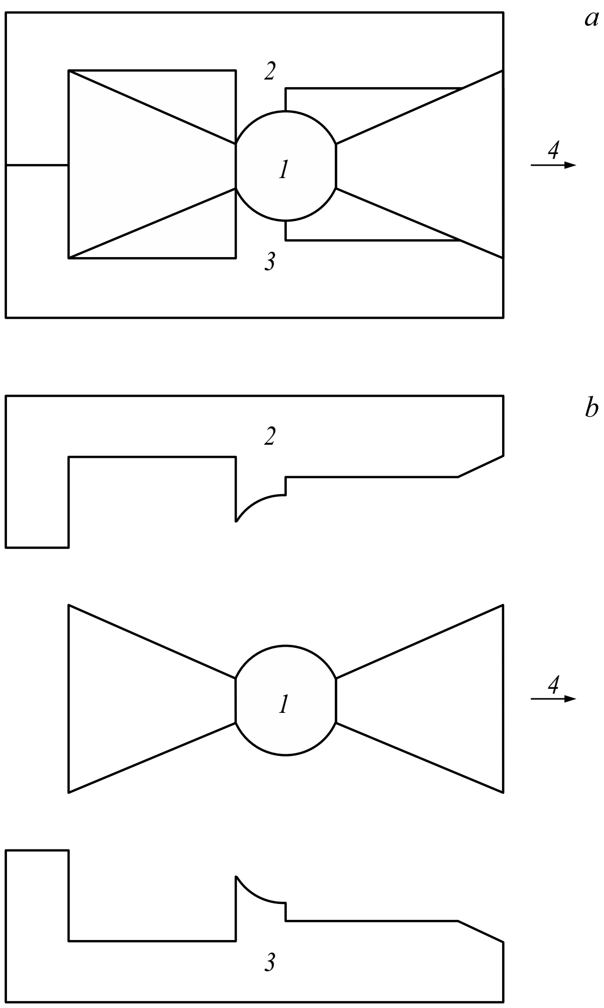

Figure 2. Variant of a sabot for acceleration of a fast ignition, direct compression target, consisting only of a fuel capsule and cones. The sabot and the target rotate relative to the longitudinal axis. Stages before (a) and after (b) separation of the sabot parts from the target by centrifugal force: *1* — target, *2, 3* — part of the sabot, *4* — target flight direction.

with its rotation relative to its longitudinal axis has been discussed [10]. Other scenarios are also possible, such as use of springs and centrifugal force. Fig. 2 shows, for simplicity, a sabot of two parts separated by centrifugal force. It is possible that sabots of this type should consist of three or more parts [10].

The discussed accuracy of target delivery to the irradiation region is a value of a few tenths of a millimeter to 1 cm [1,6,10–12]. It is suggested that when relatively heavy targets are delivered that comprise an X-ray radiation confinement shell, or/and cone(s), or/and some other structural elements, it may be achieved by rotating the target [10,11,13,16,19]. Rotation is also capable of providing the necessary orientation of a target with cones (see, for example, [10,11,13], where a similar problem is discussed in relation to indirect initiation targets).

Choice of the option to rotate a target by stabilizing rotation will be determined by target design, primarily by the ablator material. Papers [10,13] refer to linear acceleration of targets in rifled barrels, which is consistent with the basic conventional precision shooting technique [54,55]. Probably, for all targets with plastic and other relatively durable ablators, use of a rifled or twisted-channel barrel is optimal. Some indirect initiation and fast ignition, indirect compression targets can be accelerated in a rifled barrel either without a sabot [6] or in a sabot that rotates with the target. Options with a sabot appear to be optimal, particularly because of the ability to provide little contamination and wear of the barrel through the choice of sabot material and design; for economic reasons, multiple use of the sabot is preferred.

The twisted channel of the barrel is either a cylinder with an elliptical or oval base twisted around an axis, or a prism also twisted around an axis [54,55]. It is possible that use of such barrels would provide little wear of barrel channels and sabots, as well as very high target delivery accuracy [54], which would simplify their irradiation (see, for example, [10,18]). Little wear of barrel channels and sabots will also be achieved by using cheaper rifled barrels and sabots with protrusions entering the rifling. Such a sabot would be analogous to the bullets used in 19th century with „lugs“ [55].

In paper [50], an ablator for direct initiation targets is proposed consisting of plastic foam filled with deuterium tritium ice and covered with thin layers of plastic and gold (in the example shown, these layers are 1 μm and 300 Å respectively). Such ablators can also be used in fast ignition, direct compression targets with one or two cones. Feasibility of rotational stabilization of such targets with a rifled or twisted channel barrel is still unclear due to the unknown maximum allowable value $\varepsilon_{\max}$ of angular acceleration ε. Strictly speaking, $\varepsilon_{\max}$ depends on the target design and temperature (see below) and is not yet known for any ablator under any conditions, but the ablator proposed in paper [50] can be expected to have the lowest mechanical strength and, as a consequence, $\varepsilon_{\max}$.

When the sabot with the target moves in a rifled barrel or a twisted channel barrel ε is unambiguously determined by barrel parameters and a_l. In principle, a situation may arise where a limit on $\varepsilon_{\max}$ will result in a limit on a_l and thereby on the minimum length of such barrel L required to achieve the selected v_t and rotation speeds of the sabot and target Ω. Larger values of L, such as about 10 m, would be acceptable [14,51], but minimization of L is desirable from an economic point of view. Therefore, it may be advisable to use a sabot consisting of two parts, one of which is spun along with the target at permissible ε before the linear acceleration of the sabot and target, and the other serves to provide linear acceleration. In selecting Ω achieved during initial spinning, it may be necessary to account for decrease of Ω as linear acceleration progresses. Examples of high-speed throwing with pre-spin of the accelerated object are presented in paper [56].

2.2. Targets with a protective shell

Highly effective protection of any target will be provided when it is delivered to an area near the center of the reactor chamber in a shield container [14,40] or a sabot used for target acceleration as well [2]. Two types of containers have been considered. Irradiation of the fuel capsule through the walls of the first type container and the sabot is not possible [2,14]. Immediately prior to irradiation of the target such a container or sabot is opened [2,14] or removed (in the latter case the container is opened from the side opposite to the direction of flight) [14]. The second type container includes a thin protective plastic shell through which the fuel capsule is irradiated (the whole shell or its irradiated parts are transformed into plasma) [14,40]. If necessary, a frozen gas coating may be applied on the shell, which evaporates by the time the fuel capsule is irradiated [14]. Since the second type container is mechanically bonded to the fuel capsule or/and other structural elements of the target, its structural elements, particularly the shell, may be considered as structural elements of the target; this version of the terminology is used below.

The cones of the fast ignition, direct compression target can serve as supporting structural elements for securing the shell (see [40] and fig. 3). Protruding rims of the front cones relative to the flight direction (fig. 3) transfer the impact of the sabot to the front cone during linear and angular acceleration. A similar rim has previously been proposed for a single cone target [16].

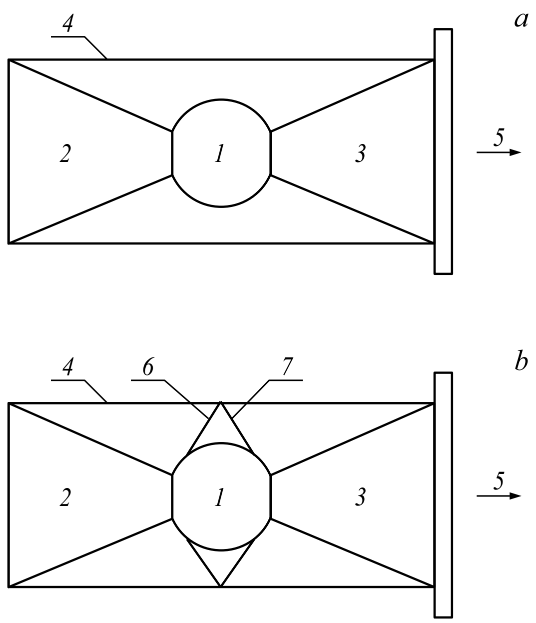

Figure 3. Fast ignition, direct compression targets with two cones, a protective shell, and a fuel capsule fixation by cones (a) or cones and membranes (b): *1* — fuel capsule, *2, 3* — cones, *4* — protective shell, *5* — target flight direction, *6, 7* — fixing membranes.

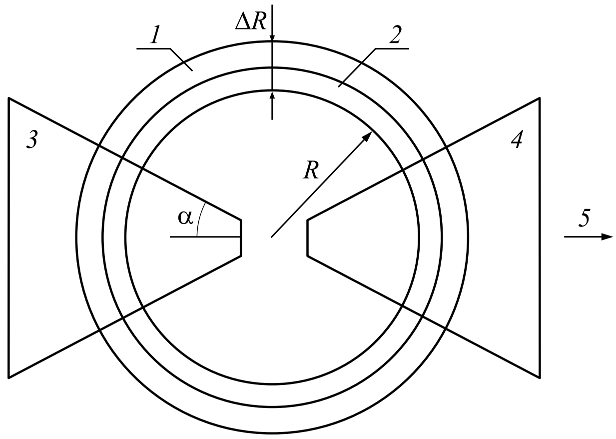

Figure 4. Illustration to calculate average pressure at the rear cone boundary with fuel and ablator: *1* — fuel, *2* — ablator, *3* — part of rear cone, *4* — part of front cone, *5* — target flight direction.

The fuel capsule of the target shown in fig. $3, a$ is in contact with the cones only. Let us estimate the average pressure p_r arising from the linear acceleration of such target at the boundary of the rear cone with solid fuel in the form of deuterium-tritium ice and ablator, proposed in paper [50]. We assume that the force acting on the capsule in the longitudinal direction from the front cone is zero; the cones, at least in the areas of contact with the ablator and the fuel, are externally identical and their generators are directed toward the center of the capsule (fig. 4). Note that another geometry of the cone boundaries with fuel and ablator has also been discussed, see, for example, [16].

The total mass m_s of solid fuel and ablator is approximately equal to

$$(4/3)\pi \cos\alpha\rho_a \Delta R(3R^2 + 3R\Delta R + \Delta R^2),$$

where α — angle between cone generator and its axis, $\rho_a \approx 0.25775\,\mathrm{g/cm^3}$ — ablator density [50], R — internal radius of solid fuel (fig. 4). Here it is taken into account that solid fuel density $\rho_f \approx 0.25\,\mathrm{g/cm^3}$ [50] is close to ρ_a. Area S_c of contact surface between rear cone and solid fuel and ablator is equal to $\pi \sin\alpha\Delta R(2R + \Delta R)$ (fig. 4). Projection of force $p_r S_c$, acting on this surface along normal line thereto, on acceleration direction is equal to $p_r S_c \sin\alpha$ (fig. 4). Comparing it to $m_s a_l$ and taking into account that $a_l = v_t^2/(2L)$ (here it is suggested that a_l is constant, see also [11]) and $R \gg \Delta R$, we get

$$p_r \approx \frac{\cos\alpha\rho_a R}{\sin^2\alpha}\,\frac{v_t^2}{L}. \qquad (1)$$

The range of p_r corresponding to the existing assumptions about the possible values of the parameters included in formula (1) is quite wide. For example,

$$p_r(\alpha = 30^\circ,\ R = 2\,\mathrm{mm},\ v_t = 100\,\mathrm{m/s},\ L = 10\,\mathrm{m}) \approx 1.8 \cdot 10^3\,\mathrm{Pa},$$

$$p_r(\alpha = 30^\circ,\ R = 2\,\text{mm},\ \upsilon_t = 400\,\text{m/s},\ L = 30\,\text{m}) \approx 9.5 \cdot 10^3\,\text{Pa},$$

$$p_r(\alpha = 25^\circ,\ R = 2.5\,\text{mm},\ \upsilon_t = 500\,\text{m/s},\ L = 10\,\text{m}) \approx 8.2 \cdot 10^4\,\text{Pa},$$

$$p_r(\alpha = 15^\circ,\ R = 3\,\text{mm},\ \upsilon_t = 700\,\text{m/s},\ L = 7\,\text{m}) \approx 7.8 \cdot 10^5\,\text{Pa}.$$

Part of this range is compatible with the expected mechanical properties of the fast ignition target fuel even when accounting for the heterogeneity of stress distribution in the deuterium-tritium ice and ablator. For example, it is assumed that the yield strength of equimolar deuterium-tritium ice is approximately $5 \cdot 10^5$ Pa at 17.4 K, which is approximately 280 times higher than the first p_r value given, and increases with decreasing temperature [11]. Cooling the fast ignition target fuel, at least to some temperature of $0 < T^f_{\min} < 17.4$ K, will also improve its compression during microexplosion initiation [29] (see also [10,11,49]). The fact that there is a restriction on cooling of the discussed fuel has not yet been established. If it does not exist or $T^f_{\min} < 4$ K, it is reasonable to cool the fuel of any fast ignition targets to a temperature close to 4 K [49].

The main expected technical difficulties of using the targets shown in fig. 3, *a* for power generation are related to the transfer of rotational torque to the fuel capsule. Apparently, for the ablator capsules proposed in paper [50] this is not possible due to the fact that at almost any ε the cones will slip in the fuel capsule, resulting in unacceptable damage thereto. Slipping of the cones in the fuel capsule seems undesirable for targets with other ablators as well. It is possible that ablators made of plastic and a number of other materials could be glued to the cones, but the problem of whether such gluing would affect compression symmetry and contamination of the fuel has not yet been resolved. Another potential solution for targets with any ablator is to replace the cones with pyramids (truncated or non-truncated) or „combined" structural elements. In one variant such structural element would be a truncated pyramid transitioning as it tapers into a cone, in another variant the pyramidal portion would be surrounded by two conical ones. The contact area with the ablator and solid fuel should correspond to the pyramidal part.

The supporting membranes of the target shown in fig. 3, *b* are similar to the membranes securing the fuel capsules of indirect initiation targets (see, for example, [10,11,57–59]). Obviously, the transition from fixation of the fuel capsule by cones alone to its fixation by cones and membranes, other things being equal, will substantially reduce the stresses arising in the materials of the capsule as a result of linear and rotational acceleration, due to an increase in the total area of the contact surfaces. At the same time, the cones will prevent the oscillations of the fuel capsule considered in paper [10] resulting from linear acceleration of the target with fixation of the capsule by the membranes alone. Strong negative effect of membranes on Y_f observed in some experiments on NIF [57–59] seems unlikely for fast ignition targets since there is no need for very high compression symmetry to ensure the formation of hot, relatively low-density plasma in the central region of the compressed fuel (see, for example, [28,29]).

The technical problems associated with the preservation of the fuel capsule during linear acceleration and spinning up of a fast ignition, indirect compression target with two cones are similar to those for the target shown in fig. 3, *b*. The main difference is that the relatively low-strength ablator proposed in paper [50] will not be used in indirect compression targets.

3. Initial selection Ω

Expected masses, diameters, and velocities of some fusion power plant targets are close to the corresponding characteristic parameters of rifled weapon bullets, particularly airguns or small-bore rifles. Given that accuracy of high-precision rifles has served as a guide to establish realistic requirements for accuracy of delivering fusion targets to the region near the center of the reactor chamber [1,10,11], we will choose as the first option of Ω the value

$$\Omega_1 = \min(\Omega_{b0}, 0.9\Omega_d, \Omega_n), \tag{2}$$

where Ω_{b0} — initial rotation speed of a bullet with close mass and diameter, Ω_d — rotation speed of the target leading to its damage under centrifugal force, Ω_n — rotation speed of the target, when noticeable negative effect of its rotation on fuel compression begins, which may not be compensated, or its compensation is unreasonable.

Note that papers [10,11] suggest that accuracy of target injectors can match or exceed the accuracy of rifles, since the injectors „shoot in vacuum" (see also [6,7,14,15]), and [10] mentions that target injectors do not require retention by a gunner. High accuracy in target delivery will be aided by high accuracy of target and sabot manufacturing [6,60], as well as constant monitoring of injector parameters and sabot quality during their repeated use.

Here is an example of using formula (2).

Paper [16] considers a fast ignition, direct compression target with a cone with a maximum outside diameter of 5 mm, mass of approximately 0.3 g and a fuel capsule with a diameter $d_c = 3.46$ mm and mass $m_c \approx 4$ mg (and the fuel capsule is described by the term „target"). Adding a second cone to this target while maintaining the mass of the fuel capsule will cause the mass of the new target to be approximately 0.6 g. An air rifle IZh-22 of 4.5 mm caliber with a rifling pitch of $s = 0.35$ m fires bullets with mass of 0.45 or 0.56 g, the initial velocities of these bullets υ_{b0} are 130 and 125 m/s respectively (rifling pitch — distance at which the rifles make a complete revolution) [61]. Since with constant s $\Omega_{b0}[\text{rot/s}] = \upsilon_{b0}[\text{m/s}]/s[\text{m}]$ [61], in the considered situation $\Omega_{b0} \approx 360{-}370$ rot/s.

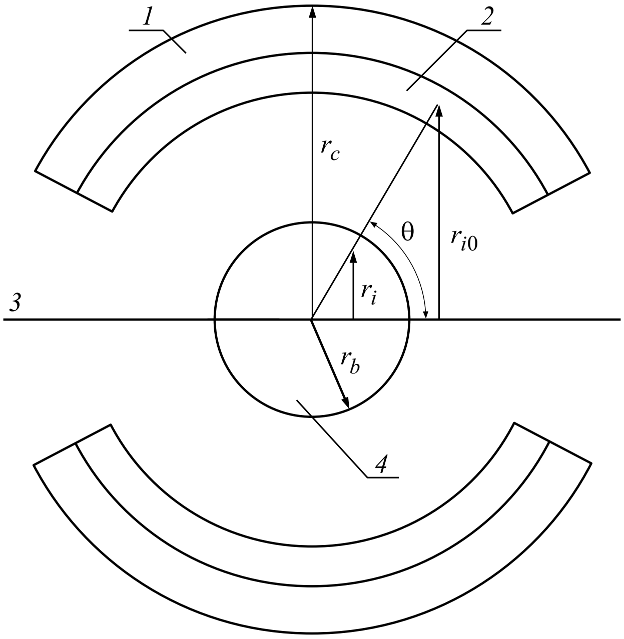

Figure 5. Illustration to calculate υ_i: *1* — ablator, *2* — uncompressed solid fuel, *3* — axis of rotation (longitudinal axis of target), *4* —compressed fuel.

When $\Omega = 370$ rot/s and the radius of the fuel capsule $r_c = d_c/2 = 1.73$ mm, the centrifugal acceleration on its outer surface will be approximately 9350 m/s^2. According to paper [11], at temperatures less than 17 K deuterium-tritium ice may withstand $a \geq 10^4$ m/s^2.

Let us evaluate the effect of the discussed rotation on the fuel compression. Let us assume that during the maximum compression stage, the fuel is an approximately homogeneous ball with a density $\rho_f^{\max}$ in the 300−500 g/cm^3 [28,29] range, the center of this ball is on the rotation axis (fig. 5) and the moment of impulse of the i-th fuel particle M_i is determined by the rotation of the target before compression begins. The latter means that $M_i = \omega m_i r_{i0}^2$, where $\omega[\mathrm{s}^{-1}] = 2\pi\Omega[\mathrm{rot/s}]$ — angular rotation speed of the target, m_i — mass of i-th particle, r_{i0} — initial value of the distance r_i between it and the axis of rotation, i.e. the longitudinal axis of the target, and the effect of rotation on the motion of this particle in the direction perpendicular to the axis of rotation is determined by the centrifugal energy $U_{ci} = M_i^2/(2m_i r_i^2)$ (see [62] and fig. 5). It can be shown that U_{ci} is equal to the kinetic energy of i-th particle as it moves with velocity $\upsilon_i = \omega r_{i0}^2/r_i$.

Let us note through $\upsilon_i^{\max}(r_i)$ the largest value υ_i at fixed r_i. It corresponds to the angle $\theta = \pi/2$ (fig. 5). Due to the fact that the solid fuel and ablator layer thicknesses are small compared to r_c (see, for example, [16,20,21,34]), the $r_{i0} \approx r_c \sin\theta$ approximation is applicable (fig. 5).

Let us note the radius of the fuel at its maximum compression by r_b (fig. 5). Let us assume that the mass of the fuel is $0.345 m_c \approx 1.38$ mg (the factor 0.345 is chosen based on the example from [50]), which corresponds to

$$r_b(\rho_f^{\max} = 300\,\mathrm{g/cm^3}) \approx 1.03 \cdot 10^{-2}\,\mathrm{cm},$$

$$r_b(\rho_f^{\max} = 500\,\mathrm{g/cm^3}) \approx 8.70 \cdot 10^{-3}\,\mathrm{cm}.$$

Using these r_b, we obtain, for example, that

$$\upsilon_i^{\max}(\rho_f^{\max} = 300\,\mathrm{g/cm^3},\, r_i \geq 0.1 r_b) \leq 680\,\mathrm{m/s},$$

$$\upsilon_i^{\max}(\rho_f^{\max} = 500\,\mathrm{g/cm^3},\, r_i \geq 0.1 r_b) \leq 800\,\mathrm{m/s}.$$

Since the compression uniformity disturbance under consideration is large-scale, and the maximum compression rate of the fuel $\upsilon_{\text{inplosion}}^{\max}$ would be of the order of 100 km/s and the allowable relative large-scale compression heterogeneity would be several percent (see, for example, [3,29,34]), the presented examples $\upsilon_i^{\max}$ make it possible to conclude that such disturbance is acceptable. Thus, if resistance of deuterium-tritium ice to centrifugal and linear acceleration is close and the center of the compressed fuel is incident or nearly incident on the axis of rotation, the Ω of the target in question can be close to Ω_{b0} of the air rifle IZh-22 bullets for any ablator material. In this case, a small, for example a few percent, decrease of Ω compared to 370 rot/s may be required only to fulfill the requirement of ensuring the safety margin of the target, described in formula (2) by multiplier 0.9 before Ω_d.

For the fuel compression variant under consideration, effect of the centrifugal force on the gas in the central region of the fuel capsule is negligible (the need to consider the possible role of this effect was noted by the reviewer). For other variants of compression, including in cone and two-sided cone targets, this effect can probably lead to a marked spatial modulation in isotopic composition of the gas in question, i.e., to dependence of concentrations of D_2, T_2 and DT on r_{i0} at low r_{i0}, corresponding to gas. To initiate of a microexplosion with formation of a „hot spot“ in a relatively low-density fuel initially fully or partially in the gas phase, such modulation seems undesirable and may be an effect limiting Ω. The target discussed here is described by parameter $\alpha = 24.5°$ (see fig. 4 and [16]). Substituting this parameter and $R \approx r_c = 1.73$ mm into formula (1) provides, for example, that $p_r(\upsilon_t = 400\,\mathrm{m/s}, L = 7\,\mathrm{m}) \approx 5.4 \cdot 10^4$ Pa, $p_r(\upsilon_t = 600\,\mathrm{m/s}, L = 15\,\mathrm{m}) \approx 5.7 \cdot 10^4$ Pa. Both results are approximately nine times lower than the yield strength of the fuel in question at 17.4 K [11].

A fast ignition, indirect compression target with two cones may be manufactured and accelerated so that part of its shell will rotate relative to the cones and the fuel capsule, thus separating, at least in part, the problems of rotational stabilization of the target flight from the problems of deuterium-tritium ice resistance to centrifugal acceleration and the effects of rotation on compression. Feasibility of this complication of targets for power generation and their acceleration scenario is currently unclear. In any case, targets of this type can be used for scientific purposes. A similar approach is used to improve the armor penetration of cumulative rounds of rifled guns [63].

Conclusion

The problems of accelerating targets with two cones and ensuring that they remain operational for a flight in a reactor chamber are quite solvable. In some cases, they are simpler than similar problems for targets without cones and with a single cone.

In the opinion of the author of this paper, the considered methods of delivering fast ignition targets with two cones to the area near the center of the reactor chamber are the most effective. In principle it is possible to correct the flight of the target before it enters the reactor chamber [10,11,17] and/or in the reactor chamber itself (the latter can be achieved by ablative pressure, see also [14]), but a detailed study of the problems associated with the correction would be feasible only in case of experimental confirmation of insufficient accuracy of delivery by the methods considered, which seems unlikely.

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Conflict of interest

The author declares that he has no conflict of interest.

References

[1] J.J. Duderstadt, G.A. Moses. *Inertial Confinement Fusion* (John Wiley and Sons, N Y, 1982)
[2] W.R. Meier. Fusion Eng. Des., **25** (1−3), 145 (1994). DOI: 10.1016/0920-3796(94)90060-4
[3] M.M. Basko, S.Yu. Guskov, A.N. Didenko, A.V. Zabrodin, V.S. Imshennik, D.G. Koshkarev, M.V. Maslennikov, S.A. Medin, S.L. Nedoseev, Yu.N. Orlov, V.P. Smirnov, V.I. Subbotin, L.P. Feoktistov, V.V. Kharitonov, M.D. Churazov, B.Yu. Sharkov. *Yaderniy sintez s inertsionnym uderzhaniem. Sovremennoe sostoyanie i perspektivy dlya energetiki*, pod red. B.Yu. Sharkova (Fizmatlit, M., 2005) (in Russian)
[4] W.R. Meier, W.J. Hogan. Fusion Sci. Technol., **49** (3), 532 (2006). DOI: 10.13182/FST06-A1165
[5] T. Goto, Y. Someya, Y. Ogawa, R. Hiwatari, Y. Asaoka, K. Okano, A. Sunahara, T. Johzaki. Nucl. Fusion, **49** (7), 075006 (2009). DOI: 10.1088/0029-5515/49/075006
[6] National Research Council. *An Assessment of the Prospects for Inertial Fusion Energy* (The National Academies Press, Washington, D.C., 2013), DOI: 10.17226/18289
[7] W.R. Meier, A.M. Dunne, K.J. Kramer, S. Reyes, T.M. Anklam, the LIFE Team. Fusion Eng. Des., **89**, 2489 (2014). DOI: 10.1016/j.fusengdes.2013.12.021
[8] A.R. Páramo, F. Sordo, D.G. Gomez, B.J. Le Garrec, J.M. Perlado, A. Rivera. Nucl. Fusion, **54** (12), 123019 (2014). DOI: 10.1088/0029-5515/54/12/123019
[9] Y. Mori, Y. Nishimura, K. Ishii, R. Hanayama, Y. Kitagawa, T. Sekine, Y. Takeuchi, N. Satoh, T. Kurita, Y. Kato, N. Rurita, T. Kawashima, O. Komeda, T. Hioki, T. Motohiro, A. Sunahara, Y. Sentoku, E. Miura, A. Iwamoto, H. Sakagami. Fusion Sci. Technol., **75** (1), 36 (2019). DOI: 10.1080/15361055.2018.1499393
[10] R.W. Petzoldt. *Inertial Fusion Energy. Target Injection, Tracking, and Beam Pointing (Ph.D. Thesis).* UCRL-LR-120192 (Livermore, 1995)
[11] R.W. Petzoldt, R.W. Moir. Fusion Eng. Des., **32**−**33**, 113 (1996). DOI: 10.1016/S0920-3796(96)00458-9
[12] D.T. Goodin, N.B. Alexander, C.R. Gibson, A. Nobile, R.W. Petzoldt, N.S. Siegel, L. Thompson. Nucl. Fusion, **41** (5), 527 (2001). DOI: 10.1088/0029-5515/41/5/306
[13] K.R. Schultz, D.T. Goodin, A. Nobile, Jr. Nucl. Instrum. Meth. A, **464**, 109 (2001). DOI: 10.1016/S0168-9002(01)00016-X
[14] M.L. Shmatov, R.W. Petzoldt, E.I. Valmianski. Fusion Sci. Technol., **43** (3), 312 (2003). DOI: 10.13182/FST03-A272
[15] E.I. Valmianski, R.W. Petzoldt, N.B. Alexander. Fusion Sci. Technol., **43** (3), 334 (2003). DOI: 10.13182/FST03-A275
[16] T. Norimatsu, D. Harding, R. Stephens, A. Nikroo, R. Petzoldt, H. Yoshida, K. Nagai, Y. Izawa. Fusion Sci. Technol., **49** (3), 483 (2006). DOI: 10.13182/FST06-A1162
[17] T. Kassai, R. Tsui. J. Phys. Conf. Ser., **112**, 032047 (2008). DOI: 10.1088/1742-6596/112/032047
[18] L. Carlson, M. Tillack, J. Stromsoe, N. Alexander, D. Goodin, R. Petzoldt. Fusion Sci. Technol., **56** (1), 409 (2009). DOI: 10.13182/FST09-A8936
[19] National Research Concil. *Assesment of Inertial Confinement Fusion Targets* (The National Academ. Press, Washington, D.C., 2013)
[20] E.R. Koresheva, I.V. Aleksandrova, O.M. Ivanenko, V.A. Kalabukhov, E.L. Koshelev, A.I. Kupriashin, K.V. Mitsen, M. Klenov, I.E. Osipov, L.V. Panina. J. Russ. Laser Res., **35** (2), 151 (2014). DOI: 10.007/s10946-018-9700-x
[21] I. Aleksandrova, E. Koshelev, E. Koresheva. Appl. Sci., **10**, 686 (2020). DOI: 10.3390/app10020686
[22] M. Tabak, J. Hammer, M.E. Glinsky, W.L. Kruer, S.C. Wilks, J. Woodworth, E.M. Campbell, M.D. Perry, R.J. Mason. Phys. Plasmas, **1**, 1626 (1994). DOI: 10.1063/1.870664
[23] V.A. Shcherbakov. Sov. J. Plasma Phys., 9, 240 (1983).
[24] L.J. Pekins, R. Betti, K.N. LaFortune, W.H. Williams. Phys. Rev. Lett., **103**, 045004 (2009). DOI: 10.1103/PhysRevLett.103.045004
[25] S.Yu. Gus'kov, N.N. Demchenko, N.V. Zmitrenko, P.A. Kuchugov, R.A. Yakhin. JETP, **130**, 748 (2020). DOI: 10.1134/S1063776120030140
[26] S.A. Bel'kov, S.V. Bondarenko, S.G. Garanin, S.Yu. Gus'kov, N.N. Demchenko, N.V. Zmitrenko, P.A. Kuchugov, R.V. Stepanov, V.A. Shcherbakov, R.A. Yakhin. JETP, **131**, 636 (2020). DOI: 10.1134/S1063776120090149
[27] S. Atzeni, M. Tabak. Plasma Phys. Contr. Fusion, **47**, B769 (2005). DOI: 10.1088/0741-3335/47/12B/S58
[28] M. Tabak, D. Hinkel, S. Atzeni, E.M. Campbell, K. Tanaka. Fusion Sci. Technol., **49** (3), 254 (2006). DOI: 10.13182/FST49-3-254

[29] S.P. Hatchett, D. Clark, M. Tabak, R.E. Turner, C. Stoeckl, R.B. Stephens, H. Shiraga, K. Tanaka. Fusion Sci. Technol., **49** (3), 327 (2006). DOI: 10.13182/FST06-A1152

[30] M. Temporal, R. Ramis, J.J. Honrubia, S. Atzeni. Plasma Phys. Contr. Fusion, **51**, 035010 (2009). DOI: 10.1088/0741-3335/51/3/035010

[31] M.L. Shmatov. JBIS, **62** (6), 219 (2009).

[32] L.P. Feoktistov. V sb.: *Buduschee nauki* (Znanie, M., 1985), vyp. 18, s. 168−198. (in Russian)

[33] S.Yu. Gus'kov. Quantum Electronics, **31** (10), 885 (2001).

[34] S.Yu. Gus'kov. Plasma Phys. Rep., **39**, 1 (2013). DOI: 10.1134/S1063780X13010017

[35] S. Atzeni, M. Temporal, J.J. Honrubia. Nucl. Fusion, **42** (3), L1 (2002). DOI: 10.1088/0029-5515/42/3/101

[36] M.L. Shmatov. Fusion Sci. Technol., **43** (3), 456 (2003). DOI: 10.13182/FST03-A291

[37] M.L. Shmatov. Laser Part. Beams, **29**, 339 (2011). DOI: 10.1017/S0263034611000425

[38] G. Velarde, O. Cabellos, M.J. Caturla, R. Florido, J.M. Gil, P.T. Leon, R. Mancini, J. Marian, P. Martel, J.M. Martinez-Val, E. Minguez, F. Mota, F. Ogando, J.M. Perlado, M. Piera, S. Reyes, R. Rodriguez, J.G. Rubiano, M. Salvador, J. Sanz, P. Sauvan, M. Velarde, P. Velarde. Report UCRL-CONF-208155 (LLNL, Livermore, 2004)

[39] M.L. Shmatov, M. Kalal. Fusion Sci. Technol., **61** (3), 248 (2012). DOI: 10.13182/FST12-A13538

[40] M.L. Shmatov. In: *Pathways to Energy from Inertial Fusion: An Integrated Approach*. IAEA-TECDOC-1704 (IAEA, Vienna, 2013), p. 127.

[41] S. Hain, P. Mulser. Phys. Rev. Lett., **86** (6), 1015 (2001). DOI: 10.1103/PhysRevLett. 86.1015

[42] J.M. Martinez-Val, S. Eliezer, M. Piera, P.M. Velarde. AIP Conf. Proc., **406**, 208 (1997). DOI: 10.1063/1.53520

[43] B.J. Albright, M.J. Schmitt, J.C. Fernández, G.E. Cragg, I. Tregillis, L. Yin, B.M. Hegelich. J. Phys. Conf. Ser., **112**, 022029 (2008). DOI: 10.1088/1742-6596/112/2/022029

[44] J.C. Fernández, B.A. Albright, K.A. Flippo, B.M. Hegelich, T.J. Kwan, M.J. Schmitt, L. Yin. J. Phys. Conf. Ser., **112**, 022051 (2008). DOI: 10.1088/1742-6596/112/2/022051

[45] N.G. Basov, I.G. Lebo, V.B. Rozanov, V.F. Tishkin, L.P. Feoktistov. Quant. Electron., **28** (4), 316 (1998). DOI: 10.1070/QE1998v028n04ABEH001219

[46] I.G. Lebo, E.A. Isaev, A.I. Lebo. Quant. Electron., **47** (2), 106 (2017). DOI: 10.1070/QEL16277

[47] G.V. Dolgoleva, I.G. Lebo. Quant. Electron., **49** (8), 796 (2019). DOI: 10.1070/QEL16953

[48] J. Zhang, W.M. Wang, X.H. Yang, D. Wu, Y.Y. Ma, J.L. Jiao, Z. Zhang, F.Y. Wu, X.H. Yuan, Y.T. Li, J.Q. Zhu. Phil. Trans. R. Soc. A, **378**, 20200015 (2020). DOI: 10.1098/rsta.2020.0015

[49] R.B. Stephens, M. Key, W. Meier, R. Moir, M. Tabak. Report UCRL-JC-135800 (LLNL, Livermore, 1999)

[50] S.E. Bodner, D.G. Colombant, A.J. Schmitt, M. Klapish. Phys. Plasmas, **7** (6), 2298 (2000). DOI: 10.1063/1.874063

[51] T. Norimatsu, K. Nagai, T. Takeda, T. Yamanaka. *Proc. 2nd Inertial Fusion Sciences and Applications 2001* (Kyoto, Japan, 2001). Eds. K.A. Tanaka, D.D. Meyerhofer, J. Meyer-ter-Vehn (Elsevier, Paris, 2002), p. 752.

[52] E.H. Stephens, A. Nikroo, D.T. Goodin, R.W. Petzoldt. Fusion Sci. Technol., **43** (3), 346 (2003). DOI: 10.13182/FST43-346

[53] I.G. Lebo, I.V. Popov, V.B. Rozanov, V.F. Tishkin. Quant. Electron., **25** (12), 1220 (1995). DOI: 10.1070/QE1995v025n12ABEH000570

[54] *Text Book on the Theory of the Motion of Projectiles; the History, Manufacture, and Explosive Force of Gunpowder; the History of Small Arms; the Method of Conducting Experiments; and on Ranges* (H.M. Stationery Office, London, 1863)

[55] V. Fedorov. *Evolyutsiya strelkovogo oruzhiya* (Voenizdat, M., 1938), ch. I. (in Russian)

[56] P.V. Kryukov. Int. J. Impact Eng., **23**, 501 (1999). DOI: 10.1016/S0734-743X(99)00099-8

[57] S.R. Nagel, S.W. Haan, J.R. Rygg, M. Barrios, L.R. Benedetti, D.K. Bradley, J.E. Field, B.A. Hammel, N. Izumi, O.S. Jones, S.F. Khan, T. Ma, A.E. Pak, R. Tommasini, R.P. Town. Phys. Plasmas, **22** (2), 022704 (2015). DOI: 10.1063/1.4907179

[58] D.S. Clark, C.R. Weber, D.C. Eder, S.W. Haan, B.A. Hammel, D.E. Hinkel, O.S. Jones, A.L. Kritcher, M.M. Marinak, J.L. Milovich, P.K. Patel, H.F. Robey, J.D. Salmonson, S.P. Sepke. J. Phys. Conf. Ser., **717**, 012011 (2016). DOI: 10.1088/1742-6596/717/1/012011

[59] J.E. Ralph, T. Döppner, D.E. Hinkel, O. Hurricane, O. Landen, V. Smalyuk, C.R. Weber, J. Bigelow, B. Bachmann, D.T. Casey, D. Clark, S. Diaz, S. Felker, B.A. Hammel, S.F. Khan, A. Nikroo, A. Pak, P.K. Patel, D.A. Callahan, J. Sater, P. Springer, M. Stadermann, C. Walters, M. Havre, P.L. Volegov. Phys. Plasmas, **27** (10), 102708 (2020). DOI: 10.1063/5.0017931

[60] S.W. Haan, D.A. Callahan, M.J. Edwards, B.A. Hammel, D.D. Ho, O.S. Jones, J.D. Lindl, B.J. MacGowan, M.M. Marinak, D.H. Munro, S.M. Pollaine, J.D. Salmonson, B.K. Spears, L.J. Sutter. Fusion Sci. Technol., **55** (3), 227 (2009). DOI: 10.13182/FST08-3501

[61] P.A. Gusak, A.M. Rogachev. *Nachalnaya voennaya podgotovka (spravochnoe posobie voenruka)* (Narodnaya Asveta, Minsk, 1975), 2-e izd., dop. i pererab. (in Russian)

[62] L.D. Landau, E.M. Lifshits. *Mekhanika (Teoreticheskaya fizika. T. I)* (Nauka, M., 1973), 3-e izd., pererab. i dop. (in Russian)

[63] *Kumulyativniy snaryad. Sovetskaya voennaya entsiklopediya* (Voenizdat, M., 1977), t. 4, s. 525. (in Russian)