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Application of beryllium deuteride as a material for laser X-ray target shells

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Abstract. **The target ignition under the conditions corresponding to the National Ignition Facility (USA) was investigated. Beryllium deuteride BeD_2 with a small admixture of copper was considered as the target shell material. The shell parameters and the profile of a target-irradiating X-ray pulse were selected, which ensure the DT-fuel ignition. The total fusion energy release of the target was shown to amount to $\sim$ 19 MJ for the optimal choice of its parameters, which corresponds approximately to the fusion energy release of the target with a beryllium shell.**

Keywords: *laser X-ray targets, beryllium deuteride*.

1. Introduction

The target choice for the ignition in future high-power laser facilities is a rather complicated mutliparameter problem. Maximising the energy release in the thermonuclear DT-fuel combustion for a minimal laser energy input into the target imposes stringent requirements on the profile of the heating pulse and on its matching to the shell parameters (mass, diameter, thickness, etc.). In particular, two target versions are presently considered for the National Ignition Facility (NIF) [1]. These targets offer approximately equal performance from the viewpoint of fusion yield, but differ not only in the shell material, but also in the profile of the heating pulse.

The first target proposed in the Lawrence Livermore National Laboratory (LLNL) [2] is a spherical plastic capsule (polyethylene with a density of about 1 g cm^{-3}) 2.2 mm in diameter containing DT ice with a mass of 0.21 mg. The target acceleration by an X-ray pulse with a peak temperature of 300 eV was considered in Ref. [2]. The second target proposed in the Los Alamos National Laboratory (LANL) [3] is a beryllium capsule (with a shell material density of about 2 g cm^{-3}) also 2.2 mm in diameter with the DT ice mass of 0.21 mg inside. This target is accelerated by an X-ray pulse with a peak temperature of 330 eV. Since the X-ray radiation paths in beryllium and polyethylene are rather long (compared to the shell thickness), small amounts of a high-Z element were added to the shell material in both cases. Specifically, in the LLNL target, the additions of bromine with a particle density of 0.25 % and of oxygen with a particle density of 5 % were used, while in the LANL target, copper with a particle density of 0.9 % was added.

Despite the significant difference between the parameters of the two targets and X-ray pulses used for their irradiation, the energy release was almost the same in both cases (15 MJ for the plastic target and 21 MJ for the beryllium one). The choice of one or other target for real experiments is in fact determined by other factors, such as the technological efficiency of the target production, the simplicity of filling shells with DT fuel, the possibility of checking the state of the target during its storage and transportation, etc. That is why of certain interest is the search for other materials that could serve as the shell material and would possess several technological advantages over conventional targets.

Yu.A.Merkul'ev of the P.N.Lebedev Physics Institute [4] raised the question as to whether beryllium deuteride (BeD_2) can be used as the shell material for targets intended for igniting the thermonuclear fuel. In particular, the authors of paper [4] considered the possibility of obtaining transparent shells of beryllium deuteride, which permits checking the quality of DT ice in cryogenic targets. However, the density of beryllium deuteride BeD_2 ($\sim$ 0.8 g cm^{-3}) is significantly lower than the density of pure Be ($\sim$ 1.8 g cm^{-3}). For fixed parameters of the pulse irradiating the shell, the characteristics of shock waves generated when the beryllium deuteride shell is heated by the absorption of X-rays can differ significantly from the characteristics of shock waves in a pure beryllium shell.

Furthermore, the radiation paths in the shells of pure beryllium and beryllium deuteride can also differ significantly, resulting in differences in their heating and, hence, in differences in their shell acceleration dynamics. This brings up the question as to whether it is possible to compress the DT fuel, which is enclosed in a beryllium deuteride shell, to the required density at which ignition would occur. In this paper, we outline some results of numerical investigations of the operation of targets with a BeD_2 shell.

2. Formulation of the problem and results of calculations

A cryogenic target similar in design to the target for the NIF [3] was taken as the starting one for our numerical

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analysis. The target is a spherical shell with a layer of the DT ice frozen onto the inner shell surface (Fig. 1a). We will call the target enclosed in a beryllium shell with a 9 % admixture of copper, which is shown schematically in Fig. 1a, a standard target. In our calculations, the beryllium shell was replaced with a BeD_2 shell of about the same mass. Because the density of copper-doped beryllium deuteride is more than two times lower than the density of copper-doped beryllium ($\rho_{Be+Cu} \sim 1.9$ g cm^{-3}) and depends on the concentration of copper in the range $\rho_{BeD_2+Cu} = 0.766 - 0.86$ g cm^{-3}, its thickness was increased by about a factor of two to retain the total mass of the target and the shell (Fig. 1b).

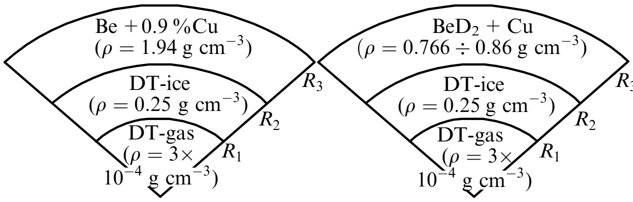

Figure 1. Target proposed at the LANL [3] for the NIF with a beryllium shell ($R_1 = 0.087$ cm, $R_2 = 0.095$ cm, $R_3 = 0.1105$ cm) (a) and target in which the beryllium shell is replaced with a beryllium deuteride shell ($R_1 = 0.087$ cm, $R_2 = 0.095$ cm, $R_3 = 0.1253$ cm) (b).

We calculated the compression and energy release dynamics of a spherical target with the above parameters using the SNDP code [5]. The radiative gas-dynamic calculations were performed in the spherically symmetric two-temperature approximation with the inclusion of thermal conduction and a nonequilibrium spectral diffusion of X-ray radiation. The numerical model took into account the electron–ion relaxation, the nonequilibrium and nonstationary kinetics of ionisation and excitation by electrons in the average-ion approximation [6], and also the thermonuclear reaction kinetics with the inclusion of α-particle transfer in the multigroup diffusion approximation with flux limitation [7]. The transfer coefficients, the spectral plasma emittance and the absorption coefficients of X-rays, and also the equations of state of matter were calculated using the average occupation numbers of the electronic levels of a multiply charged ion within the framework of the average-ion model [6, 8].

We calculated a target with a Cu-doped BeD_2 shell irradiated by an X-ray pulse with a Planck spectrum. We used in our calculations the same time dependence of the pulse temperature as for a standard target, which was proposed in Ref. [3] as a promising target for the NIF (Fig. 2, the solid curve). In this case, the energy of X-rays incident on the target was ~ 0.9 MJ. The copper dopant concentration in the shell (in the number of particles) was 0.9 %. In this calculation, the thermonuclear energy release was only 7.94 kJ, i.e., the target was not ignited. Hereafter, we call the thermonuclear energy release only the part of the total energy released in the fusion reaction which is accounted for by α-particles, because it is α-particles that are efficiently decelerated in the compressed DT fuel and heat it. We neglected the deceleration of neutrons and their energy in the calculation of the thermonuclear heating of the DT fuel. It is well known that α-particles account for

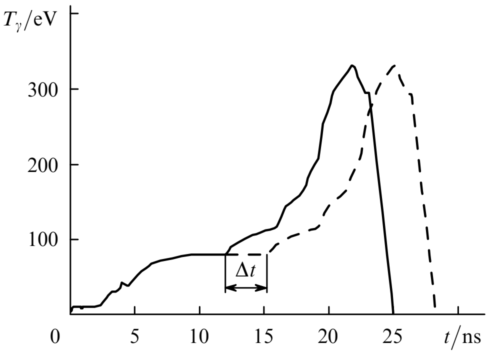

Figure 2. Time dependences of the temperature T_γ of the X-ray pulse accelerating the target.

approximately 19 % of the total energy released in the DT fusion reaction.

As a check, we calculated the combustion of the standard target ignited by the same X-ray pulse (see Fig. 1a). The energy release in this calculation was 4.16 MJ and the target was ignited. The total fusion energy for this target was 21.9 MJ in accordance with the results obtained in Ref. [3].

An analysis of the calculations revealed that the primary reason why the target with a BeD_2 shell was not ignited was a significant undercompression of the DT fuel. As a result, the fuel parameter $\langle \rho R \rangle$ ($\langle \rho R \rangle = \int_{\text{over DT-fuel}} \rho \mathrm{d}r$) at the instant of maximum compression lowered by nearly a factor of two (from 1.06 g cm^{-2} for the standard target to 0.6 g cm^{-2} for the target with a BeD_2 shell). Varying the copper density does not bring about any increase in the energy release, and the BeD_2 target was not ignited (see the first column in Table 1, which gives the calculated energy release in a series of simulations with different X-ray pulse delays Δt at different copper concentrations). Therefore, the reduction of the fuel parameter $\langle \rho R \rangle$ is not related to the different heating of the shell by X-rays.

Fig. 3 shows the spatial density distributions in the shell (BeD_2 + 0.9 % Cu) and the DT ice at different instants of time. One can see that the shock waves travelling through the shell and the DT ice are strongly noncoordinated. The second shock wave catches up with the first one rather rapidly (at the instant of time $t = 16$ ns), long before the first

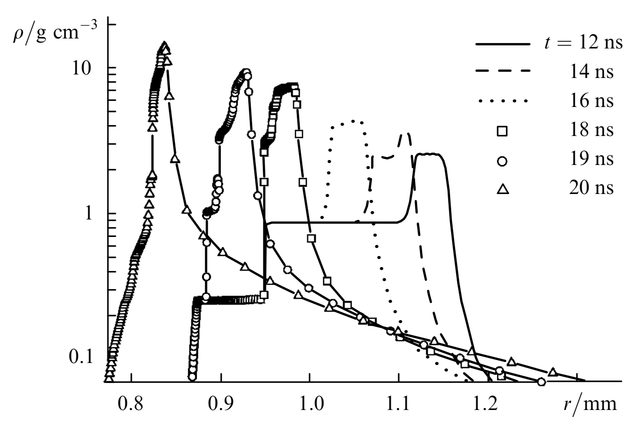

Figure 3. Spatial density distributions in the shell (BeD_2 + 0.9 % Cu) and the DT ice at different instants of time.

Табл.1. Energy release (in megajoules).

Concentration of Cu (%)	Pulse delay/ns						
	0*	2	2.5	3	3.25	3.5	4
0.0	–	–	–	4.46×10^{-3}	4.49×10^{-3}	–	–
0.1	9.75×10^{-3}	7.65×10^{-2}	0.817	1.66	1.55	1.21	0.145
0.2	–	–	–	2.96	2.92	–	–
0.3	4.56×10^{-2}	0.425	2.78	3.40	3.44	3.27	0.484
0.4	–	–	–	3.67	3.71	–	–
0.5	–	–	0.530	3.70	3.8	3.6	–
0.6	2.18×10^{-2}	3.47×10^{-2}	–	3.26	3.68	–	0.162
0.7	–	–	4.08×10^{-2}	1.27	3.09	3.04	–
0.8	–	–	–	9.65×10^{-2}	0.650	–	–
0.9	7.94×10^{-3}	2.19×10^{-2}	–	3.66×10^{-2}	–	0.145	3.13×10^{-2}

*Initial X-ray pulse (Fig. 2, the solid curve).

shock wave passes through the shell and enters the DT ice. As a result, one strong shock wave travels through the DT ice rather than a sequence of weak shock waves. This strong shock wave introduces a considerably larger entropy into the DT fuel, which eventually results in the lowering of the DT fuel compression.

To match the transit time of the shock waves, we performed a series of calculations with different X-ray pulse delays Δt (see Fig. 2, the dashed curve) at different concentrations of copper in the shell. The results of calculations are collected in Table 1. The highest energy release equal to 3.8 MJ was obtained for the target with a shell containing 0.5 % of Cu accelerated by an X-ray pulse with the delay $\Delta t = 3.25$ ns. Fig. 4 shows the spatial density distributions of the shell and the DT ice for this calculation at different instants of time.

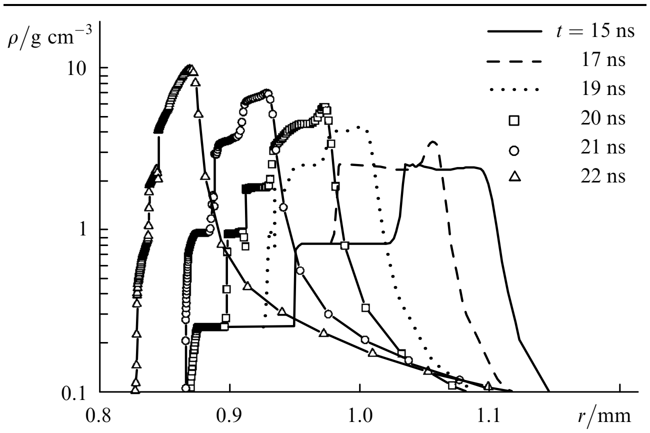

Figure 4. Spatial density distributions in the shell ($BeD_2 + 0.9$ % Cu) and the DT ice at different instants of time upon the target acceleration by an X-ray pulse delayed by $\Delta t = 3.25$ ns.

Fig. 5 shows the calculated target energy release as a function of the concentrations of copper atoms in the $BeD_2 + Cu$ shell when the target is accelerated by the X-ray pulse with the delay $\Delta t = 3.25$ ns. One can see that the concentration of copper atoms at which the target retains the operating capacity lies between 0.2 % and 0.7 %.

We performed another series of calculations by varying the thickness of the target shell containing 0.5 % of Cu; the shell was accelerated by the X-ray pulse with the delay $\Delta t = 3.25$ ns. In these calculations, the DT fuel mass and the

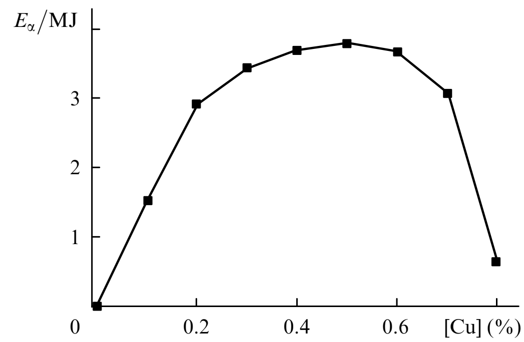

Figure 5. Energy release E_α for the target with a $BeD_2 + Cu$ shell as a function of the concentration of Cu atoms.

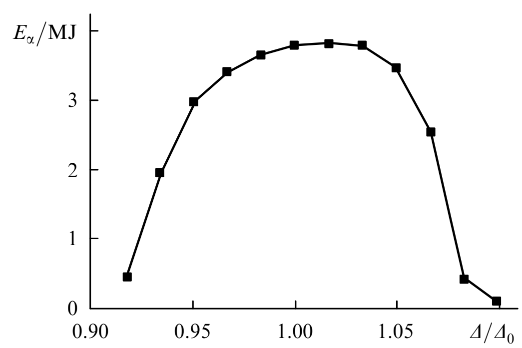

Figure 6. Energy release E_α for the target with a $BeD_2 + 0.5$ % Cu shell as a function of the shell thickness Δ ($\Delta_0 = R_3 - R_2 = 303$ μm, see Fig. 1b).

inner shell radius remained invariable. Fig. 6 shows the dependence of the energy release on the shell thickness. One can see that varying the shell thickness by 7.5 % results in the disruption of combustion.

3. Conclusions

Our study has shown that the target with a shell of beryllium deuteride offers an energy release comparable with that of the standard target, provided the X-ray pulse parameters and the copper concentration are properly chosen. In this case, the range of variation of the target parameters (the geometrical dimensions, the copper concentration) at which a stable combustion takes place is rather broad. Note that we have not considered a variety of two- and three-dimensional effects resulting in an increase in the ignition threshold and the disruption of combustion. The question of the advantages of one or other shell material from the standpoint of combustion stability of the thermonuclear fuel calls for a special investigation.

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