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Motivation and fabrication methods for inertial confinement fusion and inertial fusion energy targets

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Abstract

Popular target designs are reviewed. Possible methods of fusion target fabrication are discussed and the equipment and samples are demonstrated. The properties of the uniform and structured (cluster) materials are considered, showing the advantage of cluster material for energy conversion into soft X rays. The target materials with high content of hydrogen isotopes (BeD_2, $LiBeD_3$, or ND_3BD_3) prove to be more effective for high-power drivers in comparison with beryllium or polyimide.

Keywords: Ignition; Plasma; Target design; Target fabrication

1. INTRODUCTION

Inertial confinement fusion (ICF) concepts based on different driver application and target designs appeared soon after the start of laser-driven ICF research. In this respect, the experiments on intense heavy ion beam irradiation of targets are far beyond the experiments on laser interaction with matter (Gus'kov & Merkul'ev, 2000).

Nowadays the indirect laser-driven ICF scheme (with laser radiation conversion into X rays to heat the spherical shell target) has become a basis for the rest drivers. The targets proposed for laser illumination and for heavy ion beams are so similar that even the drawbacks of indirect laser targets could appear in the scheme with heavy ions, such as the gas-filled container in Callahan-Miller and Tabak (2000) .

Earlier proposed heavy-ion inertial fusion (HIIF) targets placed the X-ray irradiated spherical shell inside the roomy outside body with energy converters. Such a body confines the X-rays similar to the targets for the National Ignition Facility (NIF, USA). But one should remember that for indirect NIF targets, the part of absorbed energy E_{abs} is no more than 10% of E_{las}, whereas the percentage for the narrow-gap target reaches 14–16% of E_{las}. In addition, the escape of X rays is less for the tight body.

To find similar economic tight casing for heavy ions also seems very important. We propose that the spherical converter be placed right onto the fuel container as was published for laser targets (see Fig. 1; Gus'kov & Merkul'ev, 2001). We believe that this will accumulate more energy for the spherical shell than the distant empty casing. The foam is also useful for quick and precise mounting of the free-standing cryogenic shell container inside the casing.

Unlike the laser-driven ICF program, the heavy ion inertial fusion energy (IFE) program is aimed exclusively at useful civilian energy applications. Thus, from the very beginning, much attention has been paid to the reactor-size targets. Mostly the cryogenic targets (a beryllium shell with a thick DT-mixture layer) are placed inside metallic casing covered by gold from inside with the multiple inlets converters. Individually hand-made now, this construction seems problematic for mass production in the future. In cooperation with other Moscow institutes (Borisenko *et al.*, 2000, 2001; Dorogotovtsev *et al.*, 2001), we work on the construction of a target consisting of a converter placed right over the high aspect ratio (As 20–30) shell of alternative fuel with a relatively thin cryogenic layer inside as a match for the thermonuclear burn. Such a design might be appropriate for target mass production on the reactor scale. Below the corresponding technique is discussed.

2. FABRICATION METHODS FOR SPHERICAL SHELL TARGETS

Fusion targets for spherical plasma heating and compression are complex multilayer miniature constructions—hollow microspheres—done with extreme accuracy. So the wall-

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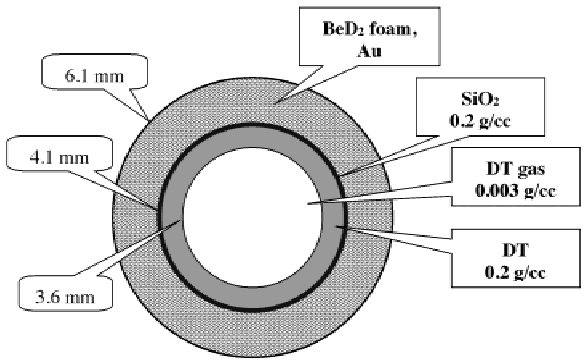

Fig. 1. Target scheme with low-density BeD_2-Au convertor (Borisenko *et al.*, 2000).

thickness deviations for the spheres of 2-mm diameter of 100-μm shell wall thickness must not exceed 0.1 μm, and the outside surface roughness must be less than 0.03 μm. The symmetry requirements are derived from compression stability conditions and are known to the factor of 2 because of laborous mathematical modeling and codes. Target and fuel masses are dependent on driver energy and pulse duration.

The thermonuclear target laboratory of the Lebedev Physical Institute started spherical target production almost 30 years ago. During the past years the unique theoretical, experimental, and fabrication opportunities were obtained. Targets, equipment for target production, and monitoring are provided. Targets, relevant equipment, and scientific reports have been sent to many scientific centers of our country and to nine countries abroad (United Kingdom, United States, France, Italy, Germany, China, India, Japan, and Poland).

Realizing the long-term program, a number of original methods for shell formation were invented. Thus the technique of rapid heating and cooling was used for target production during short-period weightlessness. For example, a ballistic furnace for making spherical shell targets for laser energies up to 2 MJ was developed and built. Besides, the new and nonexpensive installations for DT cryogenic fuel formation on the inner surface of the shell were created together with the system for cryogenic target delivery into the laser focus.

Experiments with megajoule drivers are expected to demonstrate the ignition. For that, the large targets of 1.5–4 mm should have optimized parameters such as mass, size, and thickness.

To manufacture the large shells of a fixed mass, we developed a new realization of drop tower method. Large drops (diameter > 0.3 mm) need a long drying time of more than 3 s, after which the shell is formed. This could hardly be achieved by drying in a free fall. The natural idea of freeze-drying the frozen collected initial particles emerged. The following three-step technique is proposed.

On the one hand, the developed installation is fitted for subsequent freeze-drying; on the other hand, it helps the evaporation process due to the hot dispersion of concentrated alkali silicates in water (see Fig. 2). In the first step, the helium atmosphere inside the furnace causes a five-fold drying rate increase. Partly dried particles are collected in the liquid nitrogen and are then subjected to freeze-drying at low temperatures to preserve particles' sticking (second step). The third step is to form large (1.2–1.8 mm) glass microballoons (Akunets *et al.*, 1996), from identical initial particles obtained in the two previous steps.

2.1. We propose applying alternative fuels for large shell manufacturing

The light elements and hydrogen-containing materials especially are advantageous for higher plasma stability, hot plasma burning, and decreasing the influence of shell and fuel mixing (see Table 1). The main drawback of light elements' hydrides in comparison with beryllium is lower initial ion concentration preventing the highest compression degree (and thus DT maximum density). The initial better compressibility may counter this drawback.

It is desirable to use the additional burning of shell material in the large targets, so the shell should be made of alternative fuels such as BeD_2, $LiBeD_3$, ND_3BD_3, or their mixtures. About 50% of deuteride atoms should be substituted by tritium. The technique is being developed in the Bochvar Institute for Non-Organic Materials (Russian abbreviation: VNIINM). BeD_2 shells up to diameters of 0.4 mm have been obtained by now.

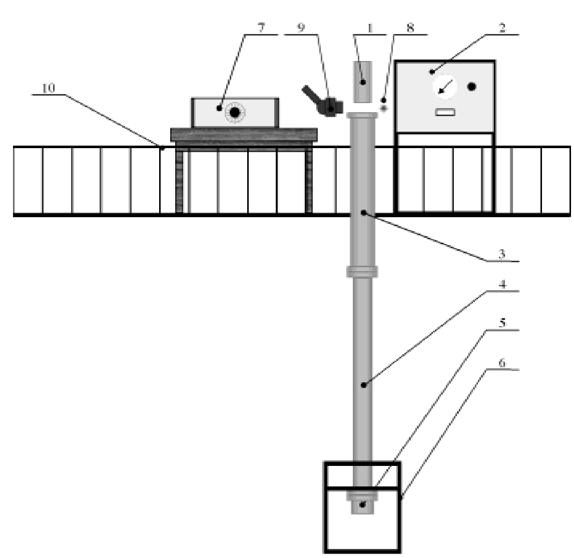

Fig. 2. Dispenser scheme. Drying zone operates with helium atmosphere and ends by collector with liquid nitrogen. 1: droplet generator; 2: gas control unit; 3: heating tube for drop drying; 4: cooling tube; 5: collection vessel; 6: support farm; 7: electronic control unit; 8: strobe light; 9: microscope; 10: balcony barrier.

Table 1. *Physical properties of alternative fuel as material for laser targets*

Properties	DT	Li_2DT	$LiBeD_{1.5}T_{1.5}$	$LiBD_2T_2$	BeDT	$(C_8D_4T_4)_n$	NBD_3T_3
Density, g/cm^3	0.25	0.92			0.826	1.3	0.99
Ions' concentration, 10^{23} cm^{-3}	0.5	1.17			1.06	0.97	
I—average $(Z+1)$ of fuel ions	2	6	5	4.5	4.5	9	5
I_t/I_{DT}		3	2.5	2.25	2.25	4.5	2.5
N_i/N_{DT}	1	2	1.67	1.5	1.5	2	1.33
Module of elasticity, GPa					27.3	2.5	
Melting temperature (glass transition), °C	19.7°K				(140)	(85)	
Boiling temperature (momentary degradation), °C	24.6°K				(350)	(570)	
Permeability of H_2, $cm^2/atm\cdot s, 10^{-10}$					<0.01	650	
Compressibility, GPa^{-1}	5	0.03			0.05	0.1–0.2	
Optical transparency	yes	yes			yes	yes	
Surface roughness, nm	30	30			10	3	
Binding energy, eV					1.5	3.6-6.3	
Number of broken hydrogen links for one tritium-emitted β particle absorbed in matter	0				≈5	≈15	

3. LOW-DENSITY FOAMS FOR FUSION TARGETS, THEIR PROPERTIES, AND FABRICATION METHODS

In the past decade much attention was paid to high-density energy interaction with low-density (structured) materials in order to uniformly distribute the heating energy. Mainly the polymers and silica aerogels were utilized (Borisenko & Merkul'ev, 1996). Only a few publications were devoted to laser interaction with low-density snowlike heavy metals; their production is discussed in Borisenko *et al.* (1994).

The future targets are believed to be cryogenic. It is well known that the uniform layer of solid DT could be only achieved by its quick cooling, which is impossible if the shell wall is thermally insulated. In addition there exists a thermal flux from tritium decay also resisting the rapid quenching of a fuel. The problem could be overcome by using metal foams instead of conventional ones, because cooling down to liquid helium temperatures increases rapidly the heat conductivity for metal foams unlike polymer ones (see Table 2).

Now we discuss the following converter—a low-density beryllium with a high concentration of a heavy element inside.

It is necessary to remember that the only metal considered as the ablator for the outer layer of an ICF target or for the whole shell is beryllium. And there is a technology route developed at VNIINM on how to obtain foam beryllium (Gorlevsky *et al.*, 1998) from beryllium hydride. Simultaneously the essential amount of the heavy element could be introduced into the structure of the foam (Dorogotovtsev *et al.*, 2001).

The rapid viscosity decrease and rather small hydrogen diffusion coefficient at glass transition temperature result in "foaming" of beryllium hydride in the course of thermolysis. The microcell structure is then obtained, hydrogen being

Table 2. *Physical properties of low density materials*

Property	Formula	Polymer	SiO_2	BeD_2	Be
Solid density, g/cm^3	ρ_0	1.07	2.2	0.76	1.85
Structure parameter $\beta \times 100$	$\beta = \rho_f/\rho_0$	0.94	0.46	1.32	0.54
Fiber diameter, d, μm	$d = l(4\beta/3\pi)^{0.5}$	0.063	0.044	0.075	0.048
Modulus of elasticity, atm	$E_f = 2\beta^2(0.23+\beta)E/3$	0.36	2.5	8	14
Strength limit, atm	$\sigma_f = 0.04\beta^2 E$	0.09	0.8	1.9	3.5
Heat conductivity, W/m·°C	$\lambda_f = 0.67\beta\lambda$	0.0005	0.0041	0.005	0.58
Heat conductivity, W/m ·°C[a]	at 20°K	0.0001	0.0005	0.0015	12.7
Heat transmission, W/m^2·°C	$\alpha_f = \lambda_f/h_f$	1	4.3	15	1750
Heat transmission, W/m^2·°C[a]	at 20°K	0.2	1	3	25,000
Heat transmission, W/m^2·°C	$\alpha = \lambda/R_0$ at 20°K	30	160	200	$3.5\cdot 10^6$
Heat transmission, °C	$T_f = T_m/(1+16\sigma\mu/d\rho RT_m)$	18	1,480	45	1,095

[a]Heat conductivity coefficients of most materials decrease with temperature, but those for metals increase.

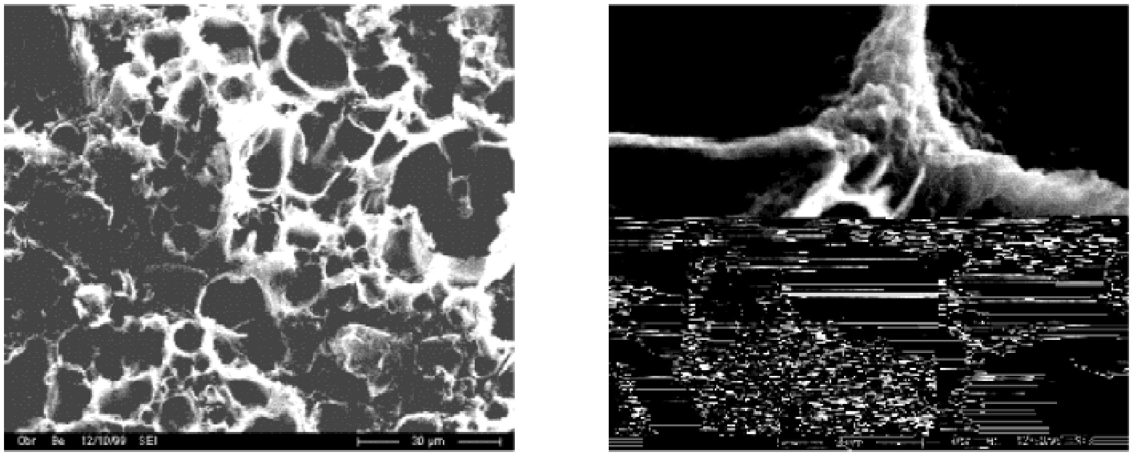

Fig. 3. SEM picture of microcellular nanoberyllium structure. Density equals to 0.45 g/cm^3.

the foaming agent. Pyrolysis in the system of BeH_2-Be fixes the structure due to the growing viscosity. The pores formed are fully open.

The Be structure of the density 0.45 g/cm^3 is presented in Figure 3. Cell walls are seen to have a thickness of ~1 μm and to form round grains of ~30–50 nm.

For intense laser radiation conversion into X rays a simultaneous codeposition of beryllium deuteride and of copper on the quartz substrate was done (see Fig. 4). The necessary profiles are possible. The obtained BeD_2-Cu layers were also foamed.

3.1. About heavy-ion energy conversion into X rays

We stressed already that the converter is one of the important elements of the HIIF target. Absorbing heavy ions, the converter material must be heated to the temperatures of which soft X rays (0.1–0.3 keV) are emitted. But the stopping range for ions grows with heating. The optimum converter should stop and extract most of the energy from the ions in the same place on the boundary of converter and the target both in the end and in the beginning of the pulse.

To solve this dilemma, the microheterogeneous converter may be used with the high-*Z* clusters distributed inside the light part (Dorogotovtsev *et al.*, 2001). The cluster size and concentration is to be adjusted so that diffusion of the heavy elements at heating provides compensation of the range growth because of the effective growing concentration of heavy element in the ion path (see Fig. 5).

The energy losses in such materials might be less than in uniform ones, but the idea is still to be proved experimentally and theoretically. Microheterogeneity can also be realized inside the foam, but then hierarchy of the concurrent processes is still more complicated and not quite clear.

4. INDIRECT CRYOGENIC TARGETS, ORIGINAL DT FILLING, AND TARGET MOUNTING INSIDE THE TARGET CASING

Most of laboratories in the world now utilize the targets mounted inside the casing. Filling is relatively slow and beta layering is used for fuel. The group headed by E.R. Koresheva in the Lebedev Physical Institute choose an alternative way (Aleksandrova *et al.*, 2000). The symmetrical even layers are formed in the free target by rapid cooling. The target is mounted after its cooling and solid layer formation.

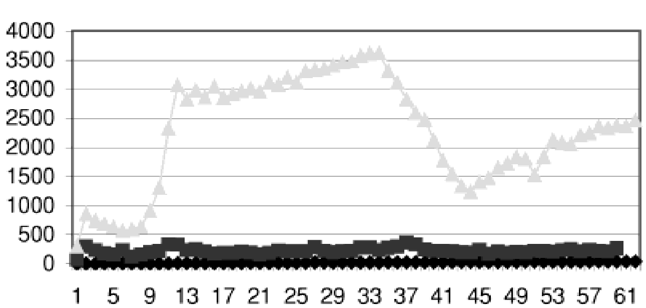

Fig. 4. Copper concentration (upper curve 1 unit: 10^{-2}%) via depth of the layer (unit: 0.25 μm) of beryllium deuteride. The lower curve: beryllium registration.

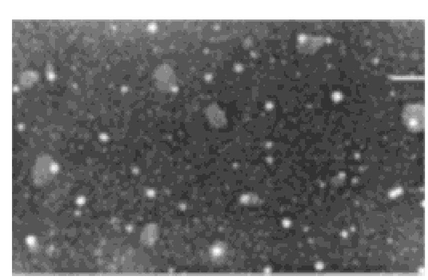

Fig. 5. Microheterogeneous material: glass seeded with Cu 0.1 μm (Borisenko & Merkul'ev, 1996; Borisenko *et al.*, 1994). Scanning electron microscope image.

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This way resulted in developing high-pressure isotope filling systems up to 1000 atm, cryogenic formation systems, and systems of target delivery to the chamber focus. The filling systems could then be placed far from the driver as well as the cryogenic target formation unit and delivery systems.

5. CONCLUSIONS

The main goal of this article was to prove experimentally (from the position of target fabricator) that within the limited and already recognized designs of large-size fusion targets, the original proposals are due as regards fuel shell production, cryogenic-target layers formation, and target delivery into the reaction chamber. These new proposals arise not from the previous experience of driver-target experiments, but from the requirements and prospects of growing driver energy both of NIF scale and of the reactor scale.

The technology routes worked out in the community of Russian scientific centers could be quickly adopted and used elsewhere due to the relative simplicity and cheapness of target delivery to the reaction chamber on the one hand and due to essential diminishing of radiation danger in the vicinity of driver, because of only 10 Ci of tritium used.

The essential features proposed to the attention of theorists are the dynamical energy converter on the surface of the fuel container, the technique using metal foam suitable for cryogenic layering, unsupported cryogenic target delivery to the hohlraum in the last moment before the shot, spherical geometry on the whole, and the use of new burning materials for the fuel shell.

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