EXTENSION OF FREE-STANDING TARGET TECHNOLOGIES ON IFE REQUIREMENTS

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Abstract

Fusion reactor studies indicate that energy generation by means of cryogenic target compression requires that targets are injected into a reactor chamber with a high repetition rate. In this regard, one of the challenges for inertial fusion energy (IFE) reactor is building the cryotarget factory. which works with moving free-standing targets. The free-standing layering technologies are the research area, which has been intensively explored at the Lebedev Physical Institute (LPI). Based on our advances, they are now at the stage of extension on a reactor-scaled target design for IFE power plant. This work is performed under IAEA Research Contract #11536/RBF. In this report, we discuss our recent and current activities for the project.

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1. Introduction

An essential feature of the entire IFE process is the need for a high repetition rate (1-10 Hz) of fusion target explosion. In this regard, the cryotarget factory (one of the fundamental building-blocks of the IFE reactor) must ensure a repetitive target fabrication and injection. Our approach to the issue is extension of the free-standing target technologies developed at LPI over the period 1993-2000 on the IFE requirements. Among them are:

1. Operation with free-standing shells at each production step in the target system (fuel filling, fuel layering and finished target delivery). This is a basic concept for the target system construction.
2. Using a batch of free-standing shells under shell filling with fuel and filled- shells transport to the layering module at 300K.
3. Cryogenic target injection from the layering module:
    - into a test chamber
    - into a pellet injector
    - onto a holder, a sabot or into a hohlraum-like unit.
4. Fall and Strike Technique (FST) for rapid fuel layering inside moving free-standing targets.

A prototype of cryotarget factory has been created at LPI using the technology combinations listed above. It has been well documented (theoretically and experimentally) that the FST forms thick solid cryogenic layers (30-to-100 μm) inside the moving targets (1 millimeter polystyrene shells) for the time less than 12 sec. These results were obtained for the shells with different values of tensile strength varied from 40 kg/cm2 to 350 kg/cm2 at 300 K. The transport process is target injection between fundamental system elements: shell container - layering module – test chamber. The targets move downward along the layering module in a rapid succession - one after another, which results in a repetitive target injection into the test chamber. Currently it is possible to generate cryogenic targets with a repetition rate of about 0.1 Hz. An experimental study of the target injection system in a rep-rate regime of six targets per second is underway. The scientific background of the related work is presented in references [1-8]

Using the FST, a layering - *plus* – delivery scheme is realized in the target system, which opens a way for repetitive target production and injection into a reaction chamber. Therefore, the research objectives of our current and near-term program aimed at (A) obtaining new information and its subsequent analyses to confirm the FST feasibility for IFE, and (B) giving the practical guide for design of IFE target factory based on FST. Of particular interest are the following issues:

- Theory, simulation program and numerical experiments for modeling the FST for reactor-scaled target production.
- Further optimization of the existing design of the layering module and support equipment, focusing on the layering module/injector assembly.
- Development of scenarios for the experimental demonstration of reactor-scaled target production by FST with regard to the required repetition rate.

The first objective is under consideration in the frame of the IAEA research contract #11536 which started at LPI in December 2000. The total duration of the contract is 1 year. In this paper we present the preliminary results obtained under the contract implementation over the period December 2000 – May 2001.

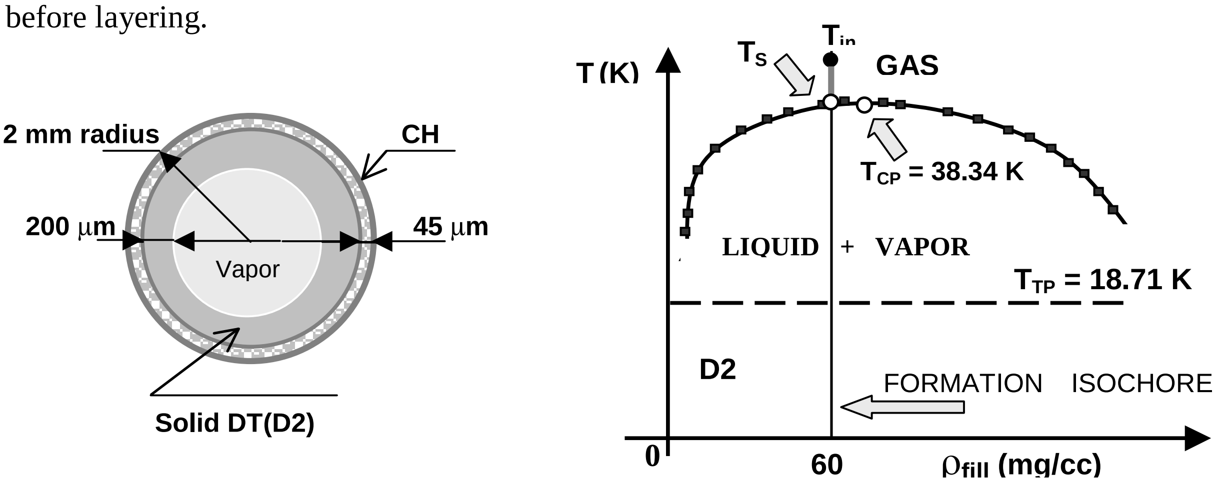
2. Extension of free-standing target technologies on IFE requirements.

Currently, there is no one universally accepted model for a reactor- scaled target. A starting point for our analysis is the model called a classical high gain target (CHGT) [9]. This target is a uniformly thick DT (D2) layer formed onto the inner surface of a polystyrene shell (CH). We discuss two configurations of CHGT. The first one is shown in figure 1. The parameters of the other are presented in Table 2 [10]. The reason for considering the CHGT is that the thermophysical and mechanical properties of the target components are well known for D2 and CH (the amount of heat transferred by conduction through the contact between the shell and the wall of a layering channel depends primarily on these properties).

In a previous work [8] we proposed a model for rapid fuel layering inside moving, free-standing targets (FST- model). The proposed FST-model can be adaptable and scalable for a rep-rate fabrication of large cryogenic targets both for new megajoule-class laser facilities and inertial fusion energy power plant.

2.1 Classical high gain target 1 (CHGT 1)

In this case our model does not require any improvements. The modeling results are most conveniently analyzed by introducing the following parameters: R is the inner shell radius; δR is the shell thickness; $\tau_{surface}$ is the time of temperature drop at the outer shell surface, which is only dependent on the experimental conditions; $\tau_1, \tau_2, \tau_3, \tau_4$ are the times of the onset and the end of fuel liquefaction and freezing, respectively; T_{in} is the target temperature before layering.



(a) (b)

FIG. 1: Classical high gain target (1): the maximal layering time is about 5.8 sec. In (a) shown is the target configuration, in (b) – formation isochore for D_2.

TABLE 1: The layering time for CHGT 1 (D2 + CH)
$(R + \delta R)$ = 3 mm, ρ_{fill} = 60 mg/cc; T_{in} = 40 K, $\tau_{surface}$ = 1sec

τ_1 (sec)	τ_2 (sec)	τ_3 (sec)	τ_4 (sec)
0.486	2.92	5.13	6.28

The calculation results for CHGT1 are given in Table 1. This has been done numerically by solving Stephen's problem for moving boundaries between the fuel phases (gas, liquid and solid). The layering time is short enough, only about 6 seconds.

Note that, at T_{in} = 40 K (i. e., at $T_{in} > Ts$, where Ts is the initial temperature of fuel separation into liquid and gaseous phases) there is a gaseous fuel phase, which requires some additional cooling time, which, in principle, is a «dead layering time». Therefore, the maximal layering time can be estimated as $\tau_{form} = \tau_4 - \tau_1$ ~ 5.8 sec (see figure 1b and Table 1). This time can be realized experimentally under target cooling along the formation isochore (ρ_{fill} = 60mg/cc) at $T_{in} = Ts$. This means that the existing layering module (currently, the time of target residence in the spiral layering channel is in the range of 6-12 sec) can be used for first experiments on a reactor target formation with a configuration similar to CHGT1. The targets will move downward along the layering module - one after another, and leave it in a rep-rate regime. This will allow to shorten the layering time per target and to demonstrate a repetitive reactor target injection into the test chamber. The demonstration of 1 mm targets injection from the layering module into the test chamber in a repetition rate of about 0.1 Hz is shown in figure 2. In our future work special attention will be paid to carrying out the process of target formation and injection automatically.

2.2 Classical high gain target 2 (CHGT 2)

For CHGT2 we also made calculations only for D2 (the left side of Table 2) because no references for some thermophysical properties were found in the case of interest (DT).

The CHGT2 is noted for its thick polystyrene shell with a low thermal conductivity (for example, in comparison with glass). In this case just the shell will define the time of reactor target formation. To carry out the calculations we have to make some changes in our simulation program for the case of thick shells. The obtained results are presented in figure 3.

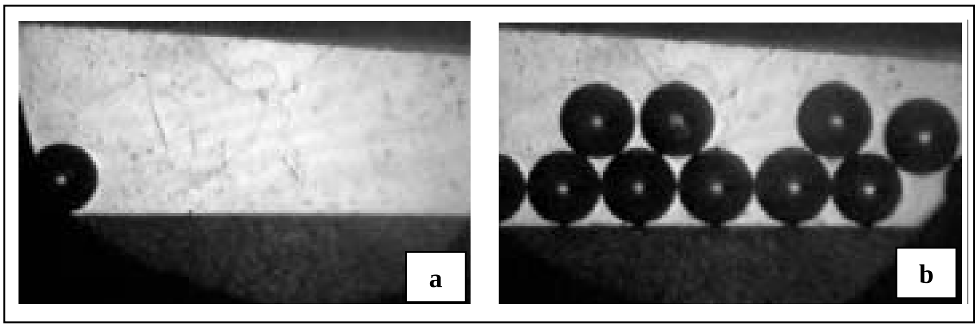


FIG. 2: Demonstration of the rep-rate target injection from the layering module into the test chamber at 4.2 K. The layering module is operated manually. In (a) 1-st target injection, t = 0; in (b) 10-th target injection, t = 100 sec

TABLE 2: Parameters of classical high gain target (2).

PARAMETERS	REQUIREMENTS FOR DT	ETSTIMATIONS FOR D2
POLYMER SHELL, mm	5.5 – 6.0	5.5 – 6.0
SHELL THICKNESS, µm	300 – 500	300 – 500
FUEL PER TARGET, mg	2.5 – 5.0	2.5 - 7.0
FUEL LAYER THICKNESS, µm	200 – 300	100-400

For a given model the calculated layering time is in the range of 66 - 127 seconds which is considerably more than in the case of CHGT1. Note, however, that under lowering $T_{in} < Ts$ one can shorten the layering time. In doing this, one should take into account the characteristic time of liquid phase existence $\tau_{3\text{-}1} = \tau_3 - \tau_1$. Since the solid layer formation goes through the liquid phase, then the value of $\tau_{3\text{-}1}$ is a key parameter and must be sufficient for layer symmetrization [8]. In other words, the CHGT2 requires further optimization of the layering procedure.

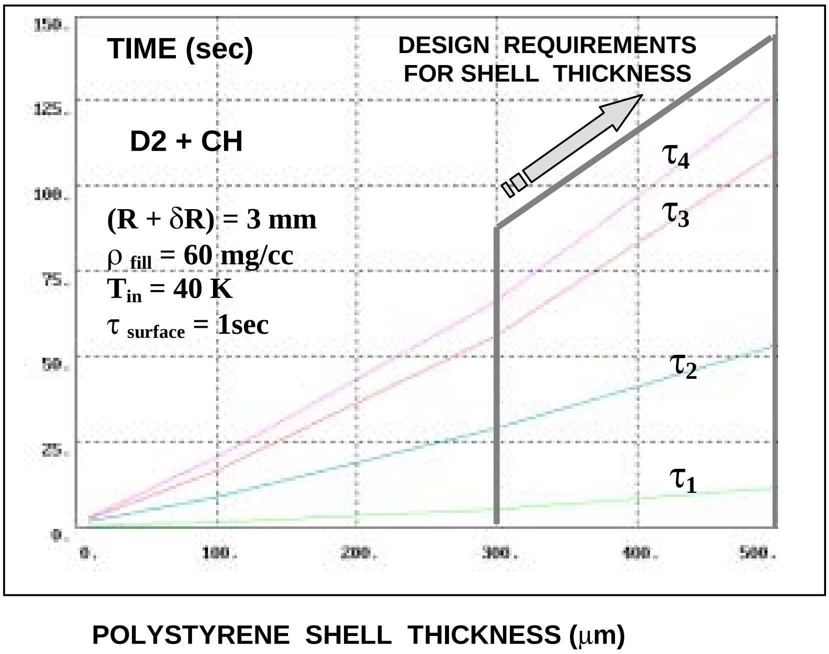


FIG. 3: Classical high gain target (2): the layering time vs. shell thickness.

For comparison purposes, we include below the calculation results relative to glass shell under the same design requirements for the other target parameters (see Table 3). In this case the layering time does not exceed 4 seconds.

TABLE 3: The layering time *vs.* shell thickness for CHGT 2 (D2 + GLASS).

$(R + \delta R)$ = 3 mm, ρ_{fill} = 60 mg/cc; T_{in} = 40 K, $\tau_{surface}$ = 1sec

δR (µm)	τ_1 (sec)	τ_2 (sec)	τ_3 (sec)	τ_4 (sec)
10	0.066	0.388	0.929	1.304
100	0.125	0.83	1.29	1.67
300	0.22	1.59	2.23	2.69
500	0.309	2.15	3.03	3.59

The obtained results indicate that in the case of reactor- scaled targets the shell properties that are of concern in the FST layering procedure are its geometry and material. In this respect, appearance of a more refined version for the target specifications is of the utmost significance for future FST optimization.

3. Conclusion

In ICF research considerable recent attention has been focused on the issue of cryogenic target fabrication for a high-energy laser driver. In this report, we have described the preliminary results on extension of free-standing target technologies on IFE requirements obtained under IAEA Research Contract #11536/RBF.

We have discussed two configurations of a classical high gain target: CHGT1 and CHGT2. The experiments on a reactor target formation with a configuration similar to CHGT1 can be carried out using the existing layering module because the calculation layering time does not exceed 6 seconds. Note that, currently, the maximal time of the target residence in the layering channel is in the range of 6-12 sec. In addition, with our target injection system we can demonstrate a repetitive reactor target injection into the test chamber.

The CHGT2 is noted for its thick polystyrene shell with a low thermal conductivity which results in a considerably long layering time: between 66 and 127 seconds, which depends on the shell thickness. This means that the existing layering module should be modified. However, discussion on the design requirements for such modification can be fruitful only after appearance of a more refined version for the target specifications.

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