Reactor-Scaled Cryogenic Target Formation: Mathematical Modeling and Experimental Results

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Abstract. In this paper we discuss our approach to resolve the issues of (1) free-standing target mass production for reactor, and (2) target survival during the delivery process. The results are presented of mathematical modeling and fabrication advantages of the layering process inside moving free-standing targets (FST) using a special rotating and bouncing (R&B) cell as a layering module. The possibility to form isotropic fine-dispersed solid fuel layers using the R&B cell with the aim of lowering the cryogenic target sensitivity to the environmental effects is under consideration as well.

1. Introduction

To achieve the implosion conditions in the inertial confinement fusion scheme, the fusion fuel contained inside a hollow polymer shell must be formed as a highly uniform and smooth solid layer (i.e.cryogenic layer). In inertial fusion energy (IFE) power plant with laser or heavy ion drivers the fuel targets must be delivered to the burn area at a rate of ~ 6 Hz. In this regard, two options are under special consideration in the recent reactor target R&D program [1], which are (1) free-standing targets mass-production, and (2) target survival during the injection process.

In this paper we discuss our approach to resolve these options.

Our approach to the issue is based on the free-standing target (FST) technologies developed at the Lebedev Physical Institute (LPI) [2-5]. According this technology the fuel-layering is realized inside moving free-standing targets owing to the following two principles:

- fuel freezing due to heat removal through the contact area between the shell and the cold substrate,
- layer symmetrization due to target random rotation.

Basing on this concept,

a prototypical system for mass-producing the cryogenic targets has been created, which operates with 5-to-25 free-standing targets at each production step. The transport process involves the target injection between fundamental system elements: shell container – layering module – test chamber. The main steps of IFE targets supply have been demonstrated with 1.0-to-1.8 mm-diam polystyrene shells using this system [2]: shells permeation filling with D_2-fuel (300-to-1000 atm at 300 K), fuel layering inside moving free-standing shells (50-to-100 μm- thick layer), and injecting the created cryogenic targets into the test chamber with a rep-rate of 0.1 Hz. The modeling results have shown that the developed technologies (i.e. FST-technologies) are promising for fabrication of reactor-scaled targets [6-8]].

Currently, a set of new FST-layering investigations is underway to elucidate the physical fundamentals underlying the efficiency of the FST-layering method in the case of reactor-scaled targets. Thereto, a special rotating and bouncing (R&B) cell was proposed and examined [6,7].

Constructively, the R&B cell is placed into an optical chamber of the layering module (see Fig. 1). A vibrating membrane is an integral part of the cell. The couple "membrane & target" is driven by an input signal generated due to a piezoelectric effect. The R&B cell operates at cryogenic temperatures, which are controlled within the rates of 0.001- 30 K/min. If we hold

fixed temperature, it is controlled in to ±0.05 K. Our experiments have shown that changing the frequency and the amplitude of input signal one can change the mode of the crystal vibration. This allows placing the target in trajectory with a given mode: rotating (R-mode), bouncing (B-mode) or mixing (R&B-mode) (see Figs.2, 3). The experiments have demonstrated that it is possible to form solid D_2-layer inside target moving in the R&B cell [6,7]. The targets for this study were CH shells of 1.2- to 1.8 -mm diameters filled up 150 - 300 atm of D_2 at 300 K. This means that, like in the FST-layering, the target cooling goes through a contact area between the target and the crystal, and this area is randomly distributed over the target surface.

In this report, we discuss the results of mathematical modeling and fabrication advantages of the FST layering technique using the R&B cell as a layering module for reactor-scaled targets.

Another critical issue connected with IFE reactor fueling is cryogenic target survival during the injection process (both inside injector and reactor chamber). Traditional approach to resolve the issue is the using of different protective means, such as target shielding and overcoating, or profiling of target support in a sabot [7, 9-11] etc.

In this report we consider additional possibility, namely, reducing the sensitivity of cryogenic target to the heat- and g- loads due to application of fuel layer with isotropic fine-dispersed microstructure.

2. Theoretical consideration of the FST-layering in the R&B cell

We start with consideration of the heat exchange per impact between a warm target and a cold substrate. Before coming to the analysis of this process, let us make several remarks:

(1) Impact is normal, i.e. we consider only the case of B-mode generation.

(2) Impact is quasi-static, i.e. the Hertzian theory of the elastic impact is valid. The reasoning behind this supposition is the results of the experiments that demonstrate a stable work of the R&B cell and a high replication at a given frequency of the input signal. It allows one to estimate the time of impact t_c using the Hertzian theory:

$$t_c = 2.943\left(\frac{15m}{16E}\right)^{2/5}(RV)^{-1/5}, \tag{1}$$

where m is the target mass, V is the target velocity at the momentum of impact, E is the Young's modulus of the shell material of the target. In addition, the change of contact area radius r with time t is given by

$$\begin{aligned} r(t) &= r_{\max}\left[\sin\pi\left(\frac{t}{2t_p}\right)\right]^{1/2}, \ 0 \le t \le t_p \\ r(t) &= r_{\max}\left[\cos\pi\left(\frac{t-t_p}{2t_e}\right)\right]^{1/2}, \ t_p \le t \le t_p + t_e \end{aligned} \tag{2}$$

where t_p is the time of plastic engagement, and t_e is the time of elastic rebound. Then the area of contact $S_c(t)$ is

$$\begin{aligned} S_c(t) &= \pi r_{\max}^2\left[\sin\pi\left(\frac{t}{2t_p}\right)\right], \ 0 \le t \le t_p \\ S_c(t) &= \pi r_{\max}^2\left[\cos\pi\left(\frac{t-t_p}{2t_e}\right)\right], \ t_p \le t \le t_p + t_e \end{aligned} \tag{3}$$

(3) During the impact the heat flow is normal to the contact area.

(4) The initial target temperature is slightly above the triple point one while minimizes the freezing time. In other words, the initial condition for the target during the cryogenic layer formation will be the following: the polymer shell contains the liquid fuel with a temperature

~ the triple point T_{TP}, which is 13.96K for H2 and 18.71K for D2. The shell itself has the same initial temperature as the fuel inside it. The substrate temperature is 4.2K.
(5) We consider the value of the relative amplitude $A=h_{max}/2R$ (where h_{max} is maximal height of target jump over the membrane, R is target radius) as the task parameter because it is experimentally proved that the given value can vary within the wide bounds from 1.5 to 10 target diameters, depending on the input signal frequency (see section 3).
Let us make some additional remarks. The main goal in modeling the cooling process of the target in R&B cell is the following: we need not only to estimate the time of fuel cooling to the solid structure, but to create a uniform cryogenic layer on the inner shell surface. What mechanism of symmetrization can we suggest in this case? As it was shown in [3,12], it is not possible to freeze liquid fuel with the required symmetry in the case of fixed (motionless) target. Nevertheless, if we use moving target we can avoid the difficulties relative to the formation of fuel ice in the fixed target. In other words, the question of symmetrization mechanism comes to the question of the way of target moving and cooling in the R&B cell. The significant peculiarity of the target moving and cooling is the discontinuous heat contact between the target and the substrate. The target trajectory has two alternative phases: (a) free fall phase and (b) collision phase. In this case the heat transfer occurs by two ways: (a) due to the radiation and (b) due to the contact heat conductivity during impact. Note that the convectional heat transmission is missing because the experiment takes place in the vacuum chamber.
We have made the calculations using the developed numerical code [3], which show that we need about 35 hours to cool a millimeter target ($R = 0.491\,\text{mm}$, $dR = 15\,\mu\text{m}$, $W = 88\,\mu\text{m}$, H2) from 14K to the layer freezing due to radiative heat transfer. The obtained result means that when solving the problem we can limit our considerations by contact heat conductivity during impact only (collision phase). In this case we can represent the fuel cooling and ice formation as a random appearance of the ice spots onto the inner surface of the shell. This is so called a "confetti" effect, which technical realization based on configuring (reflecting plates and membrane profiling) the R&B cell and influencing the process of random fuel allocation onto the inner shell surface.
Now let us find out the total amount of impacts N_{im} needed to provide the required symmetry. As we have liquid fuel at $T \sim T_{TP}$, then the formed ice does not melt and N_{im} is also the number of ice confetti-spots. Due to the central limitary theorem the relative deviation of the number of spots from the average level is $\frac{1}{\sqrt{N_{im}}}$. As a result we can estimate a degree of layer non-uniformity (NU) in percent as:

$$\varepsilon \approx \frac{100}{\sqrt{N_{im}}} \tag{4}$$

This estimation shows that we need rather large amount of impacts ($N_{im} \approx 10^4$ and more) to provide the uniformity at 1% level due to "confetti" mechanism. Thus, in the frame of our suppositions, we come to the question of heat amount estimation during a single impact between the warm target and cold substrate.
According to the Fourier` law the amount of heat Q_{out} passing through the surface element dS for the time dt is proportional to the temperature gradient $\frac{dT}{dr}$, and given by:

$$Q_{out} = k(T) \cdot dS \cdot \frac{dT}{dr} \cdot dt\,. \tag{5}$$

Here k is the heat conductivity of the shell material, $dS = \langle S(t, a_{\max}) \rangle$ is the average square of the contact area, $\frac{dT}{dr} = \frac{T_1 - T_2}{L}$ is the temperature gradient, which is realized under the following conditions: T_1 is the target temperature, T_2 is the substrate temperature, L is the effective distance for which the heat wave spreads per impact.

Taking into account that T_1 and T_2 are given then to define the heat amount transferred per impact we need to know the maximum contact area $S_c^{\max} = \pi r_{\max}{}^2$ and the distance L.

An estimation of the contact area as a function of the target parameters can be done from energy balance between the initial energy of the target mass center and the energy of shell deformation. It is assumed that a spherical shape of the shell remains unchanged, excluding its bottom segment. This segment forms a circular area of contact. The elastic contraction of the shell material in this bottom segment consumes the initial energy of the target mass center. For estimations, let us introduce two parameter χ and δ:

$$\chi = \frac{\pi r_{\max}{}^2}{4\pi R^2} = \frac{S_c^{\max}}{4\pi R^2}, \quad \delta = \frac{\Delta R}{R}, \tag{6}$$

where R is the shell radius, ΔR is the shell wall thickness. The change of the shell volume during deformation is

$$\Delta V = \delta \cdot \pi R^3 \cdot \left(\frac{1}{12} \frac{r^4}{R^4} + \ldots \right), \tag{7}$$

so that the change of energy is

$$\Delta W \approx E \cdot \Delta V \approx \chi^2 \frac{4}{3} \pi R^3 E \delta . \tag{8}$$

where E is Young's modulus.

If the shell deformation occurs during impact, then $\Delta W = \frac{mV^2}{2}$, and the parameter χ can be written in the form:

$$\chi \approx \sqrt{\frac{3mV^2}{8\pi R^3 E \delta}} . \tag{9}$$

Maximum contact area $S_c^{\max}$ for the normal impact can be estimated to from the last correlation as follows:

$$S_c^{\max} = \sqrt{\frac{6\pi m V^2}{E \Delta R}} . \tag{10}$$

Now it remained only to estimate the linear areas of the shell target L, which efficiently participates in the heat transfer. Different parts of the target will be cooled to the diverse extent per impact. Let L be distance for which the shell temperature during impact decreases in e times. It is known that the velocity of temperature leveling in the non-uniform heated body is characterizes by the thermal diffusivity coefficient $b = \frac{k}{C\rho}$ (C is thermal capacity and ρ is density of shell material). Replace in the heat conduction equation $\frac{dT}{dt} = b \frac{d^2T}{dr^2}$ differentials of time and space by small values of t_c *and* L, accordingly. After this, using this equation we can estimate the distance for which the heat wave spreads per impact. In other words we can estimate the linear size of the area involved in the heat transmission:

$$L \approx \sqrt{\frac{t_c k}{\rho C}}. \qquad (11)$$

Then the amount of heat transferred per impact will be of the form:

$$Q = 2.2 \cdot \beta(T_1 - T_2) \cdot (\frac{\pi m}{E\Delta R})^{1/2} \cdot V \cdot t_c^{1/2} \qquad (12)$$

where $\beta = (\rho C k)^{1/2}$.

We have made calculations for targets parameters of which are given in Table I. Preliminary modeling results show that using only B-mode the layering time does not exceed 30 min (see Fig.4). Using in the R&B cell from 20 to 30 targets, the layering time can be in the range 1 – 1.5 min/target. Initial target temperature is about the triple point temperature of the fuel, which is promising for layer formation with a given solid structure.

TABLE I. TARGET PARAMETERS USED IN CALCULATIONS

Targets	Parameters
ISKRA6-a	R=1460μm, ΔR=20μm, W=15μm, D_2, T_{in}=18.75K
ISKRA6-b	R=1540μm, ΔR=33μm, W=23μm, D_2, T_{in}=18.75K
CHGT1	R=2000μm, ΔR=45μm, W=200μm, D_2, T_{in}=18.75K
CHGT2	R=3000μm, ΔR=300μm, W=200μm, D_2, T_{in}=18.75K

Thus, the R&B cell can be used as a layering module for large cryogenic target formation.

3. Reduction of cryogenic fuel layer sensitivity to heat- and g- loads due to application of fuel layer with isotropic fine-dispersed microstructure.

The critical issues of target survival during the injection process (both inside injector and reactor chamber) are to withstand overload during target acceleration, and to withstand overheat during target flight inside reactor chamber. To protect fuel core from destruction it is necessary to meet two alternative requirements, namely: (1) to reduce the injection velocity with the aim of overloads reduction, and (2) to increase the injection velocity with the aim of target flight shortening. The resolution lies in the optimization of target supply scenario as well as in the reduction of fuel core sensitivity to the heat- and g- loads. One of the approaches to resolve the last feature is the optimal choice of fuel layer microstructure.

Our analysis has shown that fusion fuel must have an isotropic structure to withstand the environmental effects: excess of heat and mechanical load during target delivery to the target chamber. This requirement rests on the following reasons:

1. In the equilibrium state the solid isotopes of hydrogen are of anisotropic molecular crystals. In this case the sound speed depends on sound wave line about the crystallographic axes. For example, the difference in sound speed for single crystal of H2 makes ~ 19% [13]. In accordance with the Debye`s theory the factor of the thermal lattice conductivity *k* is in direct proportion to the value of sound speed *v*:

$$k = (1/3)Cv\Lambda$$

where Λ is the mean free pass of the phonons.

Therefore, even under conditions of spherically symmetrical target heating, the inner surface of anisotropic fuel layer becomes non-isothermal. On the Fig. 5 one can see that temperature difference on the surface of the polycrystalline H2-layer can achieve 0.2 degree and more during the process of target heating from 4.2 K to 18 K [14]. Consequently, the temperature non-uniformity initiates the fuel migration in the target cavity and results in the degradation of layer surface finish and uniformity. The estimated characteristic times of these processes are shown in Table II.

Thus, the target with isotropic finely dispersed fuel layer can withstand to the heat-loads more effectively than the target with anisotropic crystalline fuel layer.

2. It is well known that there are two different ways of obtaining the high strength materials: (a) making of zero-defects macro-crystals (single crystals), and (b) making of materials in extremely disordered state. Making of zero-defects macro-crystals is practically impossible. In the weakly disordered macro-crystals the strength goes down under defect accumulation due to the presence in such crystals the preferential planes of low glide dislocations. Quite the contrary, amorphous, fine-grained and other high dispersity materials with a large defect density (n) have no planes of low glide dislocations, and, as a consequence, their mechanical strength rises sharply, proportionally to n (see Fig.6). Thus, there is further reasoning to use fine dispersed fuel layer, namely: such a microstructure can withstand higher overloads than its crystalline analogue.

Therefore, the development of finely dispersed layer technology is in urgent need. A significant program is under way at Lebedev Physical Institute (LPI) to develop such a technology for ICF / IFE targets.

TABLE II. RESULTS OF ESTIMATIONS OF THE CHARACTERISTIC TIME OF ARISING OF 2% THICKNESS NON-UNIFORMITY (τ_1) AND OF 0.1 μm SURFACE ROUGHNESS (τ_2) in CHGT-1

T_0, K	ΔT, K	τ_1, msec	τ_2, msec	t, msec
5	0.1	$2\ 10^{10}$	$2.5\ 10^{8}$	48
18	0.01	44	$5.5\ 10^{-1}$	
18	0.1	4.4	$5.5\ 10^{-2}$	
18	1	0.44	$5.5\ 10^{-3}$	

*/ t is the time of target heating from 4.2 K to 18 K under the action of the heat flow of 12 Вт/см^2 from the reactor chamber walls: CHGT-1 parameters see Table I

Recent cryogenic experiments carrying out at LPI using the R&B cell have demonstrated (for shell diam 1.8 mm and layer thickness up to 50 μm) that the effect of vibrations with a certain frequency on fuel during its crystallization allows forming a fine-dispersed layer (see Fig.7). The comparative results of cryogenic layer formation inside the polymer microshells under action of vibrations and without this action are shown in Fig.8.

The cooling rate q is another key parameter, which has been studied in the frame of the FST-technology for layer formation with a different structure. The experience gained up to now reveals that the value of q is within $q<10^{-3}$ *K/min* for transparent fuel ice formation as a single crystal (results of [16]), and q is within $q>10^{3}$ *K/min* for solid hydrogen amorphization (results of LPI [4]).

It should be noted that amorphous and other isotropic fine–grained states of the layer are metastable phases. That means, that under heating over a certain threshold temperature T_a, an irreversible change of the layer into the coarse-grained crystalline modification with a rough free surface takes place (Fig.9). As was estimated, the characteristic time of such degradation is less than 100 μsec when the target flies inside a target chamber [17].

Fortunately, this is well known that adding a special doping to a substance can increase stability of the fine-dispersed or amorphous material [18,19]. Our experiments have shown that in this case transparent heat resistant cryogenic fuel layers can be obtained under cooling rates within $(1\text{-}3)10^{2}$ *K/min* [5,7,21]. Such solid layer is thermo stable: it does not recrystallize when the temperature is raised from 5 K to a triple point of the main component and *vise versa* (see Fig.10).

In summary, one can conclude the following:

1. Fusion fuel must have an isotropic structure to withstand the environmental effects: excess of heat and mechanical load during target delivery to the target chamber.

2. The key parameters that allow governing the fuel layer dispersity during its solidification are the following: (a) periodical mechanical action, (b) different cooling rates.

3. Adding a special doping to a fuel allows sufficiently increasing stability of the metastable fine-dispersed fuel layer. Such a fuel layer does not spoil at target heating; therefore it will not spoil during its flight at the reactor burn area.
These results can serve as the basis of a technology for reactor cryogenic target fabrication with the fuel layer of new class, which is stable with respect to the action of heat- and g-loads arising during the delivery process.

4. Conclusion

Over the past several years an important aspect of our activity was to create a system capable of filling, layering, and delivering large, free-standing, cryogenic targets that allows rapid fuel layering experiments. Our philosophy in conceptualizing the FST system is to minimize time and space for all production steps in the system and at the same time the tritium inventory. We have demonstrated a successful performance of the FST system with millimeter size targets and discussed current developments at LPI to study the feasibility of the FST for IFE applications.
Analyses of the calculations and operating system parameters have shown that we can identify key issues that require future study for each type of classical high gain targets and start the experiments on IFE target technology development based on FST layering method. An experimental program includes the usage of different layering channels – from typical ones (cylindrical or spiral) to combine with the R&B cell, which appears considerable promise for development of new layering module designs, e.g., having a shaker- like- unite. Such a layering module can hold a large amount of targets and work with them at one time. This proposal can be considered as a new FST scenario for mass-producing the cryogenic targets.
In the frame of reactor target technology development, the problem of fuel layer survival during the injection process has been studied as well. As a result, we propose a new class of fuel layer material, which is the fuel in the metastable fine-dispersed state stabilized with a special doping. It has been proved experimentally that fine-dispersed fuel layer can be formed inside microshell under variation of two key parameters (1) periodical mechanical actions (for example, vibrations inside R&B cell), and/or (2) rates of fuel cooling. The fine-dispersed layer formation and its stabilization using a small doping have been demonstrated. Application of the fine-dispersed fuel layer will allow to reduce the cryogenic fuel layer sensitivity to heat- and g- loads, and, thus, to minimize risk of target damage during the delivery process.

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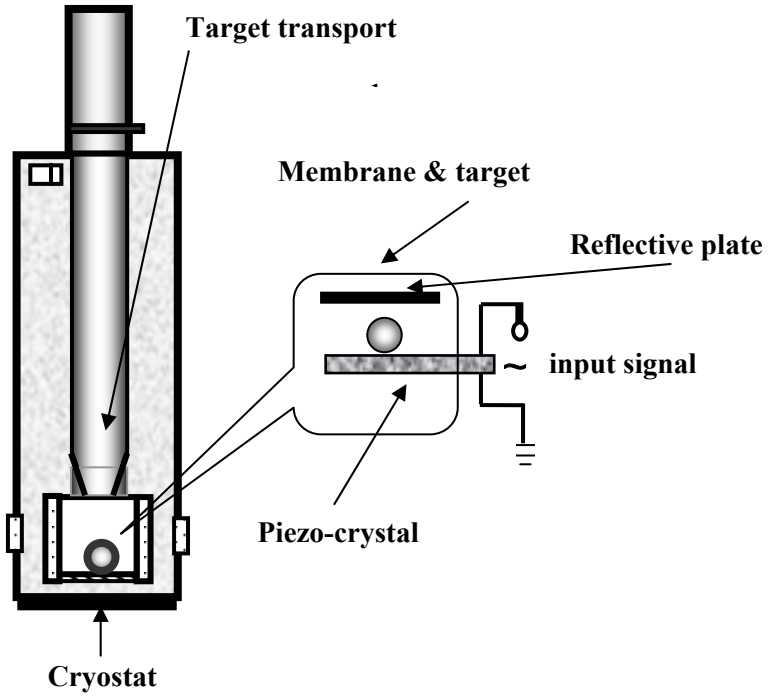


FIG.1. Disposition of the R&B cell with target inside the optical test chamber of cryostat

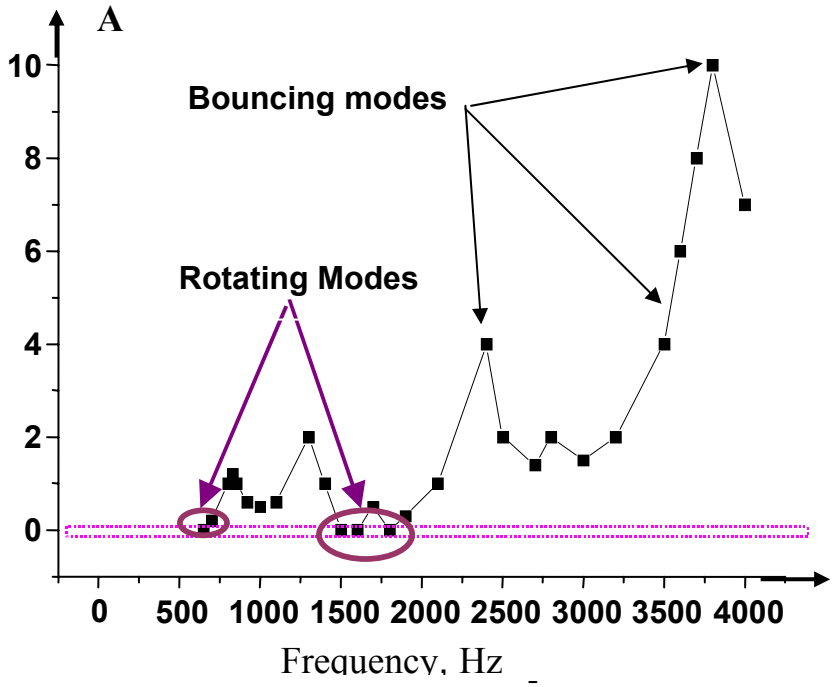
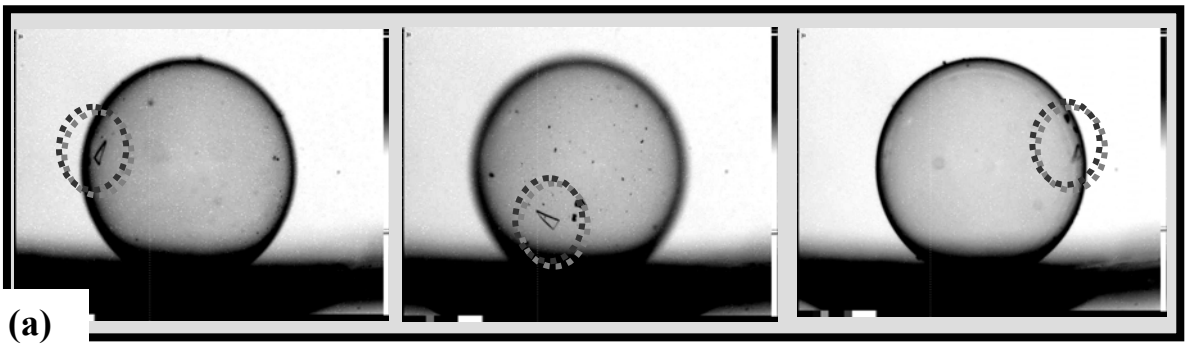


FIG.2. Generation of different modes of the target motion in the R&B cell. Temperature of the membrane is 6 K. A=h/2R, where h is the target height over the membrane, 2R is the target outer diameter.



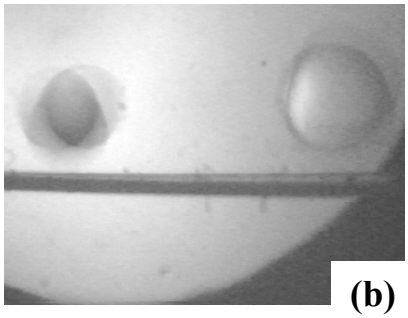


FIG.3. An experimental study with the R&B cell is designed to generate different modes of the target motion for testing and benchmarking the conditions that are applied to IFE target formation.
(a) Rotating Mode: 6 K, H=600 Hz, U=75V; (b) Bouncing Mode: 4.2 K, 3.7 kHz, 1.5 V;

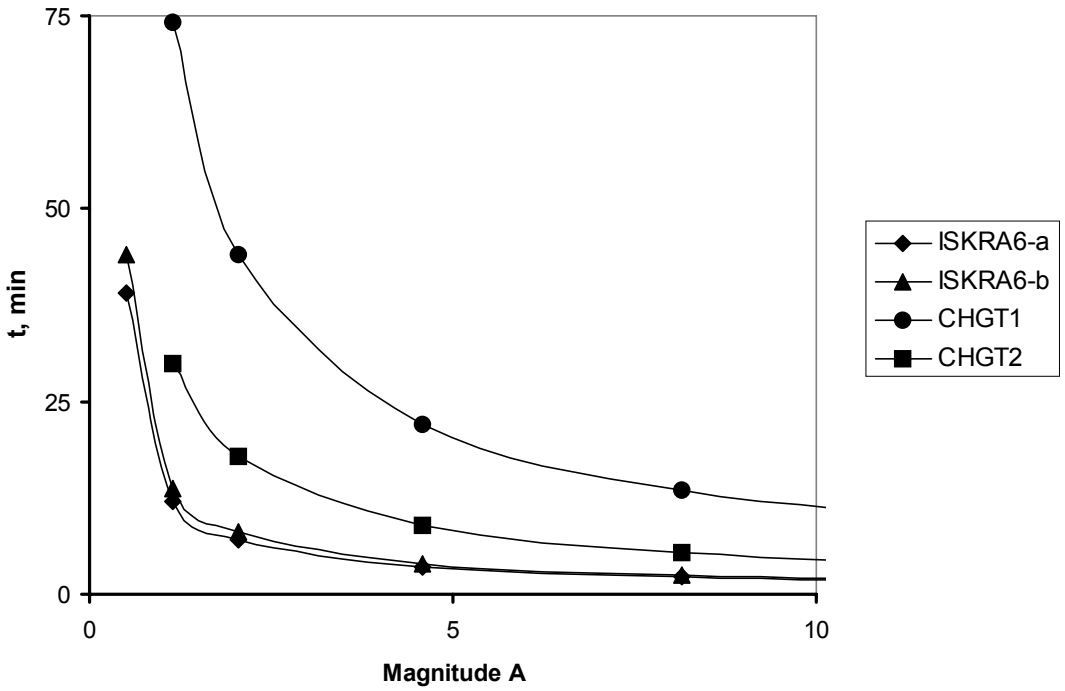


FIG.4. The layering time of different targets as a function of magnitude $A=h_{max}/2R$. The targets parameters see Table 1; $N>10^4$ for all target types.

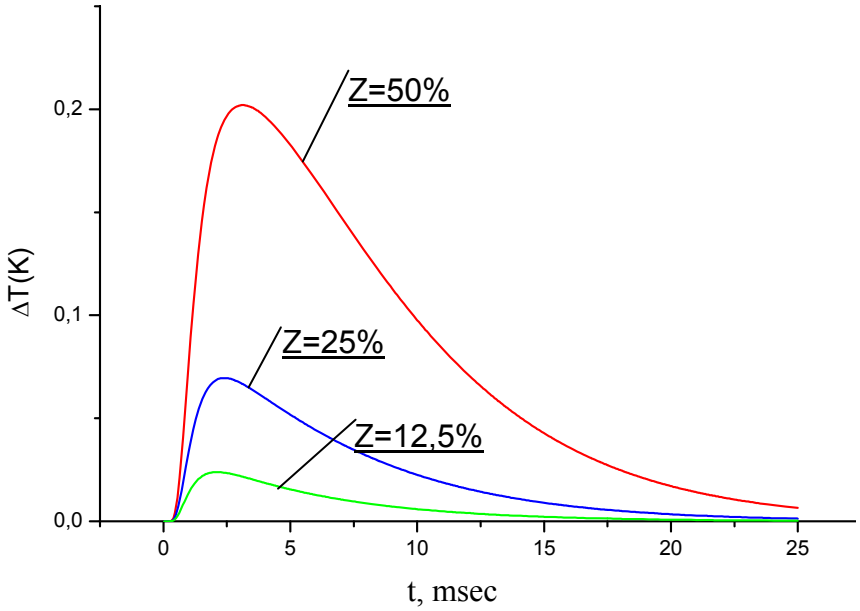


FIG.5. Evolution of the temperature difference (ΔT) between two crystals placing on the surface of isotropic H2-layer. Target is heated from 4.2 K to 18 K; main axis of the crystals are mutually orthogonal; estimations made for CHGT-1, target parameters see Table 1; Z is the crystal size with respect to the size of isotropic layer.

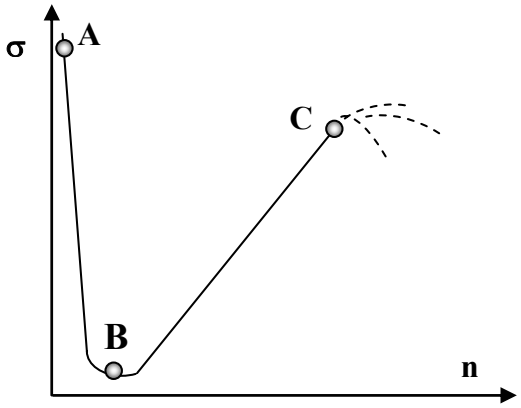


FIG.6. Strength of material σ vs the defects density n (see [15]). A is the ideal single crystal, B is the real single crystal, B-C is the fine grained (fine-dispersed) material.

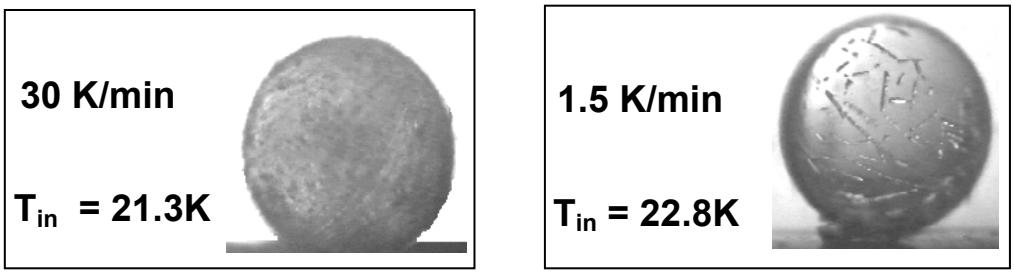


FIG. 7. The shadow images of the targets with solid D2-layers demonstrate that the rates of target cooling significantly influence the layering results: the coarse grain structure and angular non-uniformity is inherent to relatively low cooling rates (1.5 K/min), whereas higher cooling rates yield more uniform fine-dispersed ice structure.

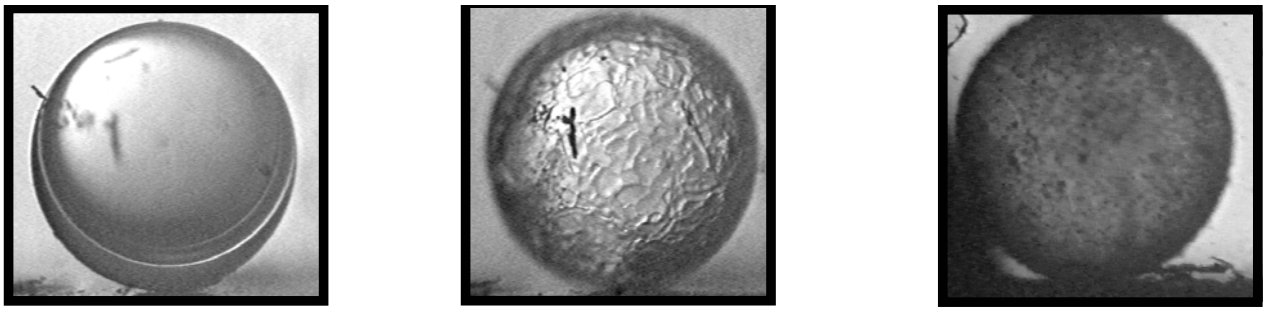


FIG.8. Cryogenic layer fabrication inside the shells with and without periodic mechanical action (vibrations) onto the polystyrene microshell (∅1.2 mm) filled with D2. Cryogenic layer average thickness is 47 μm. (1) initial state "liquid+vapor"; (2) cooling through the contact area, no vibrations (motionless target); (3) cooling while bouncing and rotating; 10 kHz, 75 V; formation time less than 60 min.

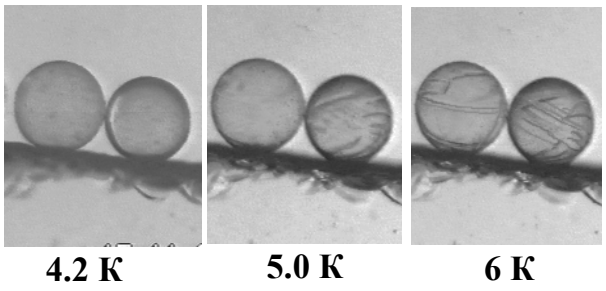


FIG.9. Re-crystallization of the transparent solid cryogenic layer under target heating to the threshold temperature T_a=5.0 K. Glass shells are 500 and 450 μm-diam, filled with pure H2.

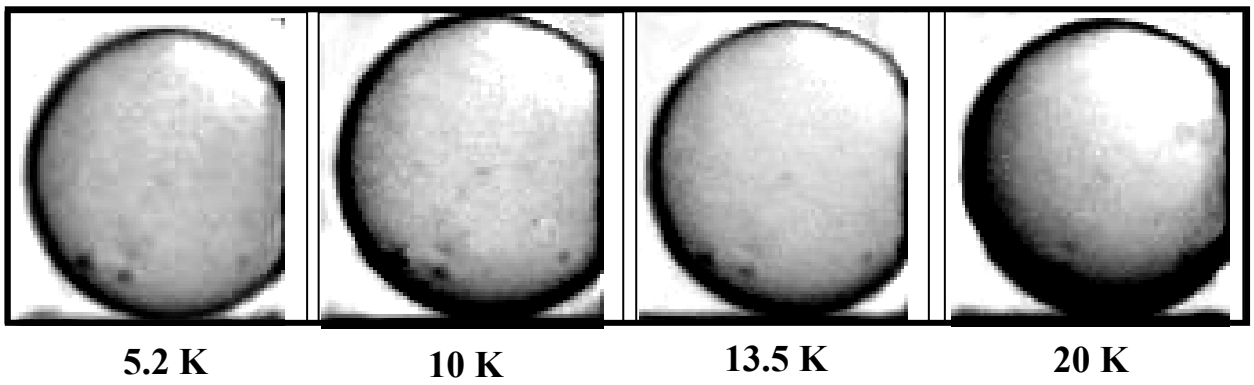


FIG.10. Fine dispersed solid layer stabilization using a special doping. Transparent cryogenic layer does not re-crystallizes under target heating in the range of 5 K to the triple point of hydrogen (T_{TP}=13.96 K). Glass microshell of ∅500 μm, cryogenic layer consist of 99.47% H_2,, (0.53±0.11)% HD, D_2<1 %