CRYOGENIC LAYER FABRICATION IN THE CONDITIONS OF HIGH-FREQUENCY MECHANICAL INFLUENCE

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■ **A central part of an inertial fusion energy (IFE) power plant is the cryogenic target with a hydrogen fuel that must be delivered to the chamber center with a high accuracy and frequency. Therefore, research fields related to the elaboration of efficient layering methods for IFE applications are rapidly expanding.**

■ **At the Lebedev Physical Institute (LPI), long-term research effort results in creation of an efficient method of fuel ice formation in moving free-standing targets, which is referred to as FST layering method.**

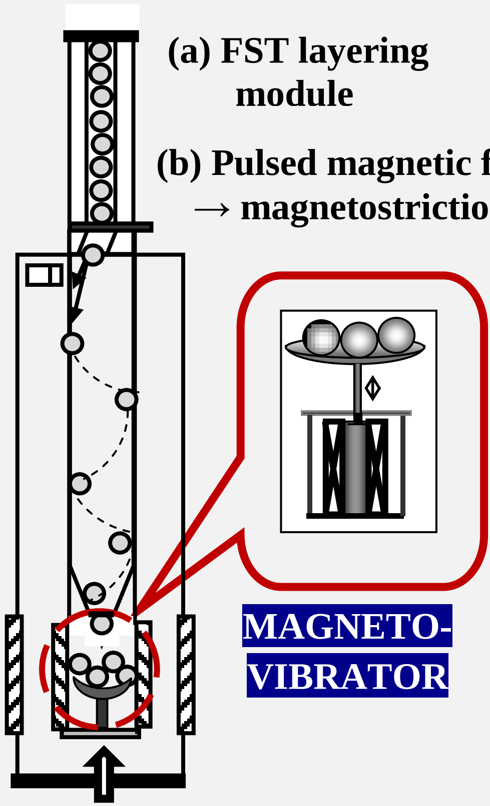
■ **A batch mode is applied, and high cooling rates (q = 1— 50 K/s) are maintained to form isotropic ultra-fine solid fuel, which exhibit peculiar and interesting mechanical and physical properties. Such fuel layers have enhanced mechanical strength and thermal stability that is of critical importance for target fabrication, acceleration and injection.**

■ **In this report, the investigation into the processes of cryogenic layer fabrication in the conditions of high-frequency mechanical influence is presented. It is carried out to reduce the cooling rates and to make the FST technology not only more efficient for reactor-scale targets (200—300-µm-thick layers), but also more reliable and inexpensive for a laser IFE power plant.**

■ **To meet the goal, the LPI has constructed a piezo-vibration module, in which the couple «membrane-&-target» is driven by an input signal due to inverse piezoelectric effect. The fuel cooling goes via the heat conductivity within a batch of vibrating targets. It allows one to modify the key experimental parameters (mechanical and thermal) for intensifying the creation of ultimate disordered structures with a large defect density, i.e., isotropic ultra-fine medium.**

■ **In the scope of the project RFBR № 15-02-02497, we report our modeling and experimental results with a piezo-vibration layering module to gain insight into the relation between the microstructure and bulk properties of the fuel, and to fabricate this fuel with a given microstructure within ICF/IFE targets.**

Development of PIEZO−&−MAGNETO units for VIBRATION influence on targets during FST layering to pursue our studies of isotropic ultra-fine layers

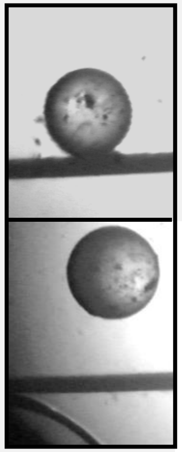


(a) FST layering module

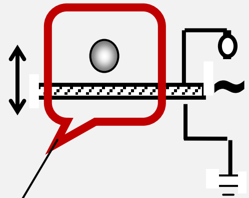
(b) Pulsed magnetic field → → magnetostriction effect

MAGNETO-VIBRATOR

Vibrator location in the cryostat



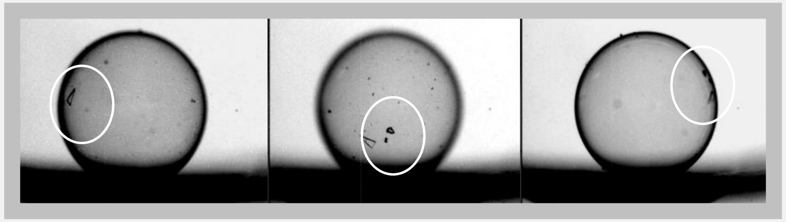
(c) Inverse piezoelectric effect



MEMBRANE-&-TARGET

PIEZO-VIBRATOR

► Bouncing (B) mode: ν = 3.7 kHz U =75 V

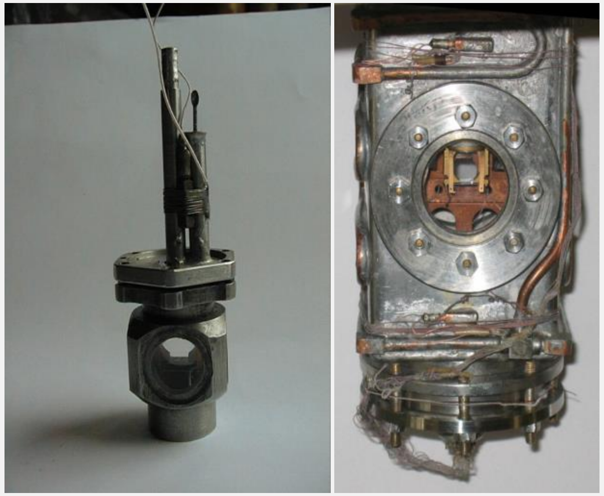


►Rotation (R) mode: ν = 0.6 kHz, U = 75 V

WORK PRINCIPLE of PIEZO-VIBRATOR

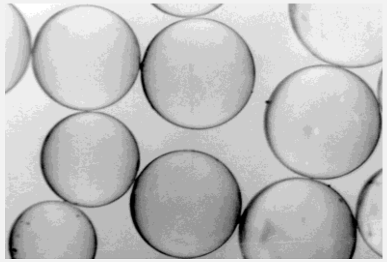
■ The couple «membrane-&-target» is driven by an input signal generated due to an inverse piezoelectric effect.

■ Modulation of the input signal impresses the required information on the «frequency-&-amplitude» carrier.

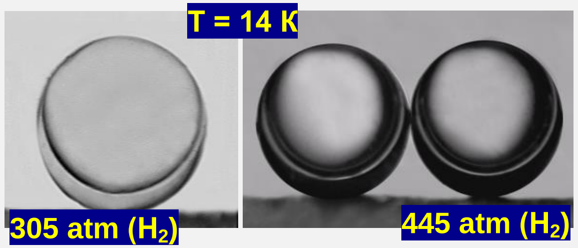


■ Test chamber with a piezo-vibrator

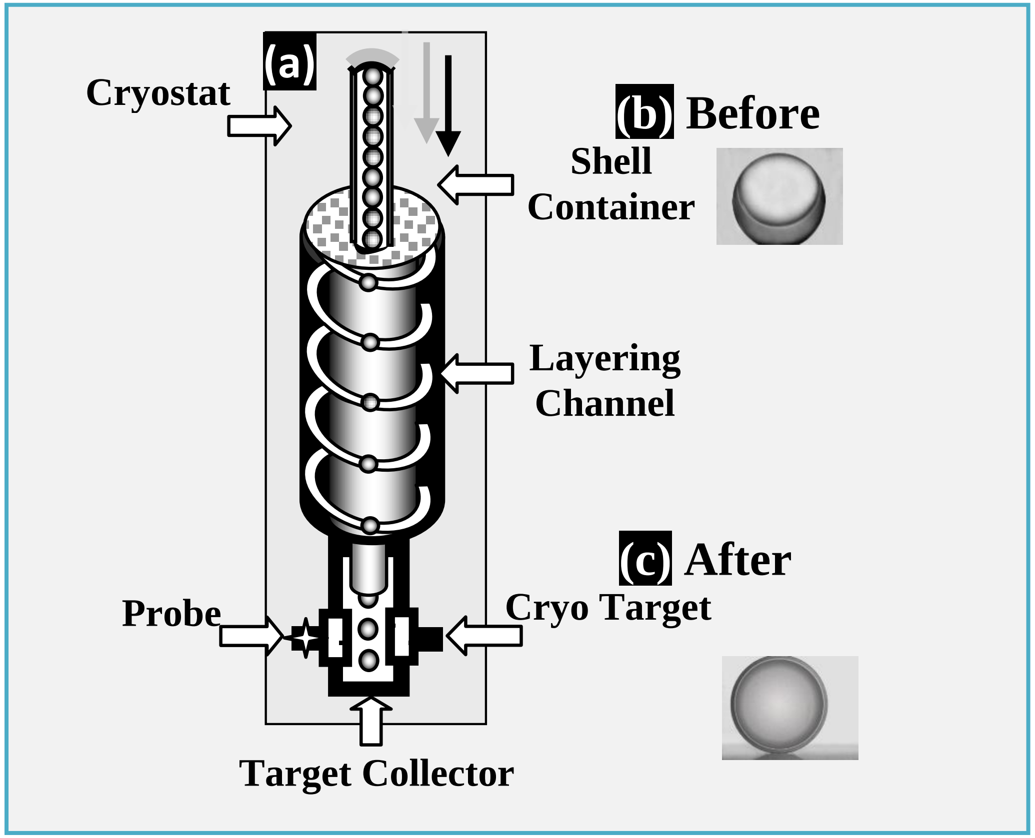
■ Empty shells

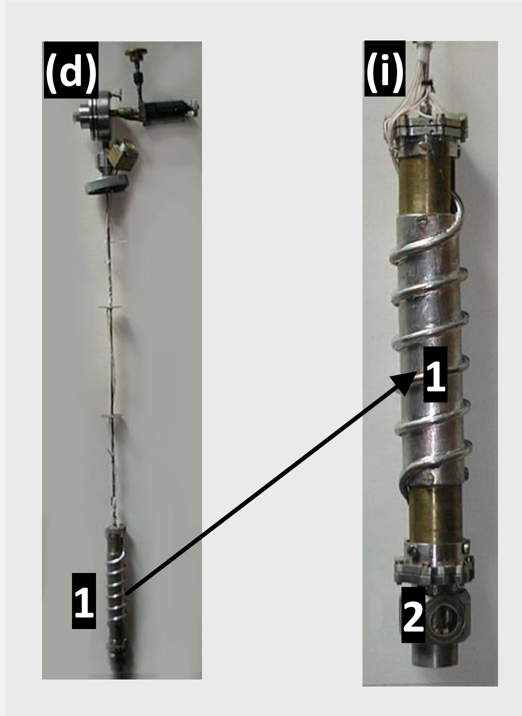


■ Shells with cryogenic fuel



This study is carried out to reduce the cooling rates and to make the FST technology more efficient for reactor-scale targets (thick cryogenic layers), and therefore more reliable and inexpensive for a laser IFE power plant





Single- spiral layering channel

■ The FST layering method provides a rapid formation of uniform fuel layers inside free-rolling targets from the hydrogen isotopes and their mixtures. A batch mode is applied, and high cooling rates ($q = 1$—50 K/s) are maintained to form isotropic ultra-fine fuel. This is conditional on two main reasons:

— to withstand the environmental effects: excess of heat and mechanical load during target delivery to the target chamber,

— to avoid instabilities caused by grain-affected shock velocity variations for meeting the requirements of implosion physics.

■ In (a): schematic of the FST-layering module; in (b): target before layering («liquid + vapor» state of fuel); in (c): target after FST layering (symmetrical solid layer); in (d): single-spiral layering channel (1), and in (i): single-spiral layering channel (1) mounted on the target collector (or test chamber) (2).

Currently, the FST-technologies development is in the scope of LPI program on creation of modular cryogenic target factory (CTF) and commercialization of the obtained results

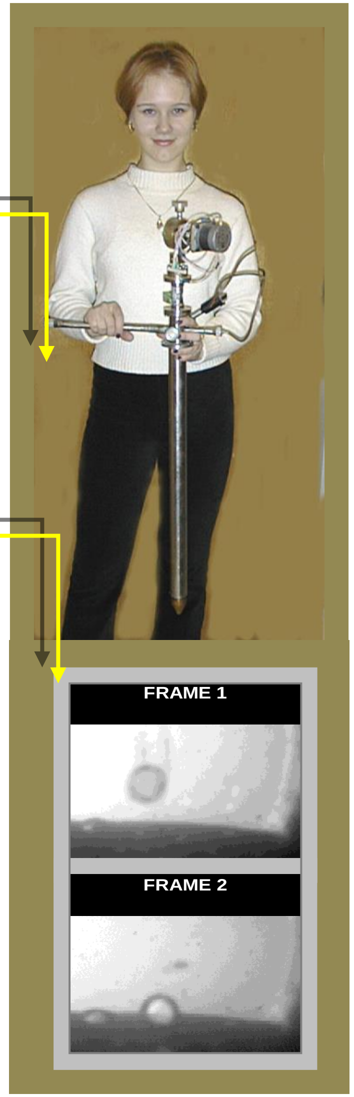
Basic elements of the FST supply system (FST-SS) have been tested using the prototypes created at LPI. This ensures a twofold benefit because it reduces the risks when creating a full-scale FST-SS, and reduces a total cost of developments.

■ Computer-aided fill facility
(~ 1000 atm at 300 K)

■ Video and tomography shell control before the shell filling with a gaseous fuel

■ Gravitational injector

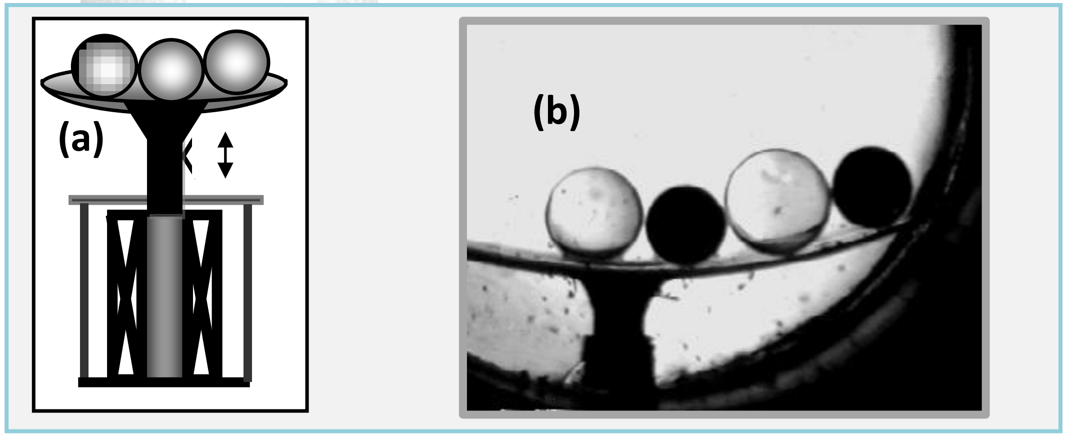
■ Target injection to the test chamber

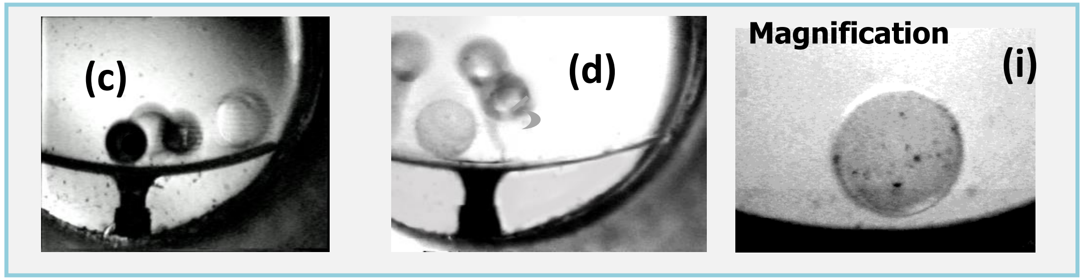


■ FST layering module for fabrication of isotropic ultra-fine fuel layers inside moving free-standing targets

■ Video and tomography control of the cryogenic targets (100 projections, 1-µm spatial resolution)

MAGNETO-VIBRATOR:
high-frequency influence on a couple target-&-membrane due to a pulsed magnetic field (effect of magnetostriction)





EXPERIMENTATION:

■ (a) Schematic diagram of high-frequency transfer on targets (or other test objects) from the membrane vibrated due to pulsed magnetic field

► Solenoid:

— parameter Iω = 600−1200 A·turn,
— pulse duration τ = 1−3 ms

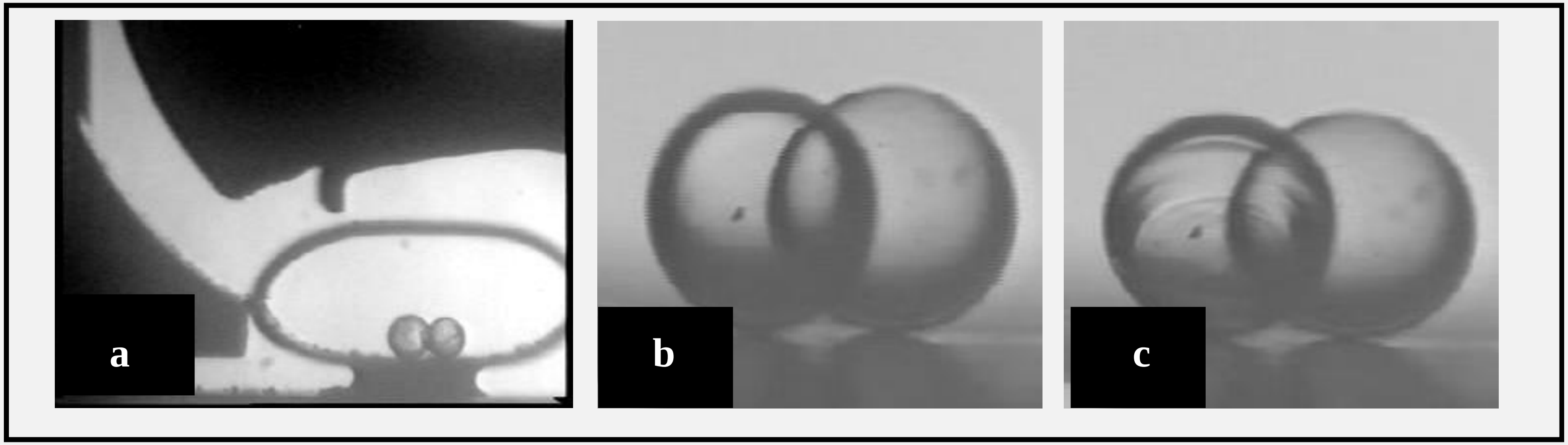
■ (b) Test objects (polymer shells and bolls) before the vibration loading

■ (c), (d), (i) Video recording during the investigations (a set of frames from different experiments)

► Further investigations have been carried out with the cryogenic PIEZO−VIBRATOR, which is a more simple and compact system for a limited volume of the cryogenic test chamber.

PIEZO-VIBRATOR:

high-frequency influence on a target due to inverse piezoelectric effect



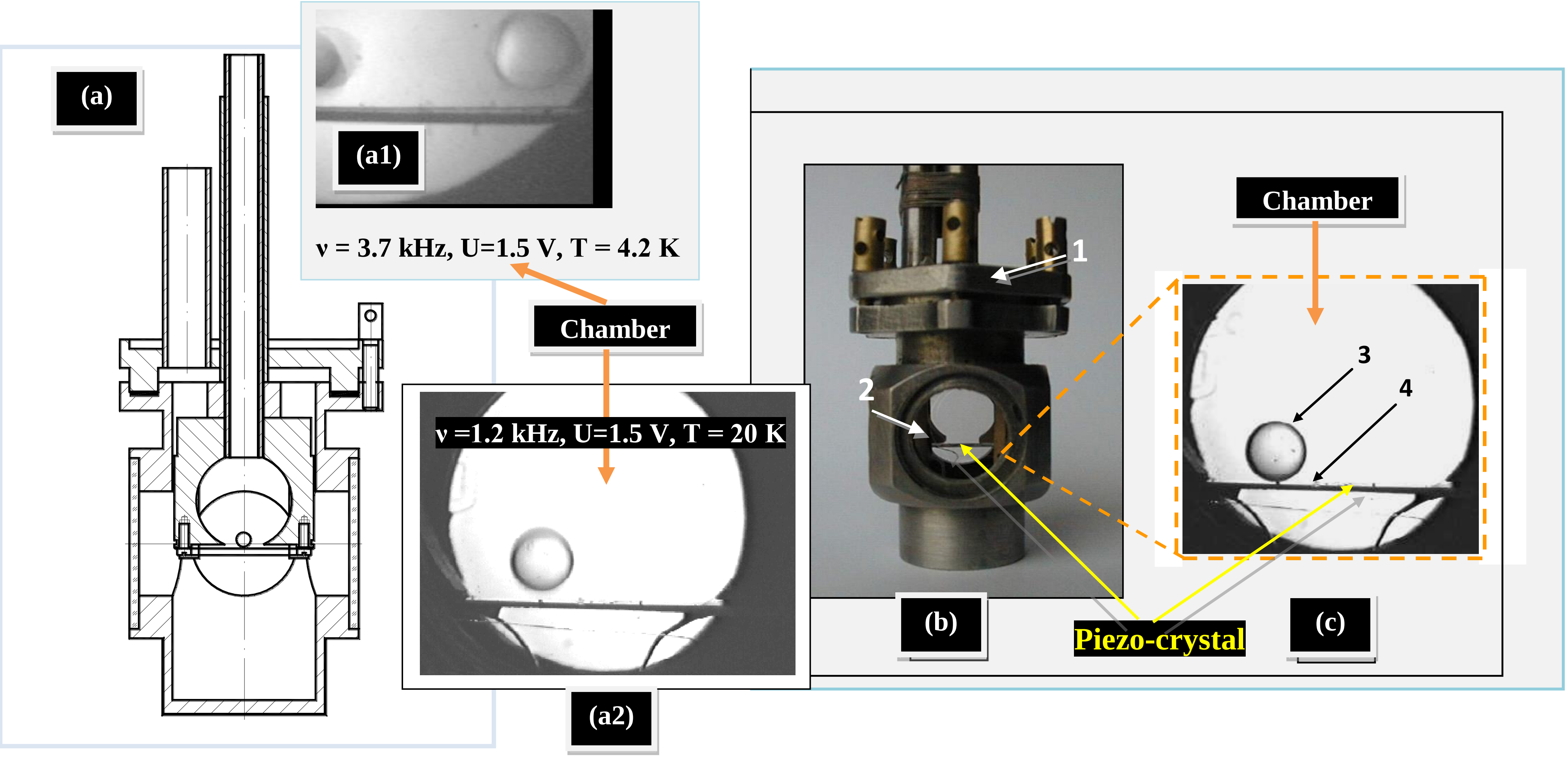
■ A general view of the optical test chamber with targets placed in the piezo-vibrator: (a) and (b) before the experimentation, and (c) at the moment of the input signal triggering.

► The spherical polymer shells made by LPI were used in the experiments:
— diameters are from ∅ = 1 mm to ∅ ~ 2 mm,
— hydrogen fuel is H_2, D_2 or their mixtures filled at 300 K from 100 atm to 450 atm.

► The shells were placed onto a membrane — a thin piezoelectric crystal with fastened edges. Then the shells were cooled to a temperature slightly above the triple point one (T_{tp}= 13.96 K for H_2 and T_{tp} = 18.65 K for D_2).

► Further cooling resulted in the fuel freezing in the presence of vibrations. The input signal amplitude was in the range of 1.5 - 75 V, and the frequency *ν* was in the range of 0.3 Hz − 3.0 MHz. The cooling rates *q* were from 10^{-5} K/s (conventional methods, e.g., β-layering method) to 1 K/s (lower value for the FST layering method).

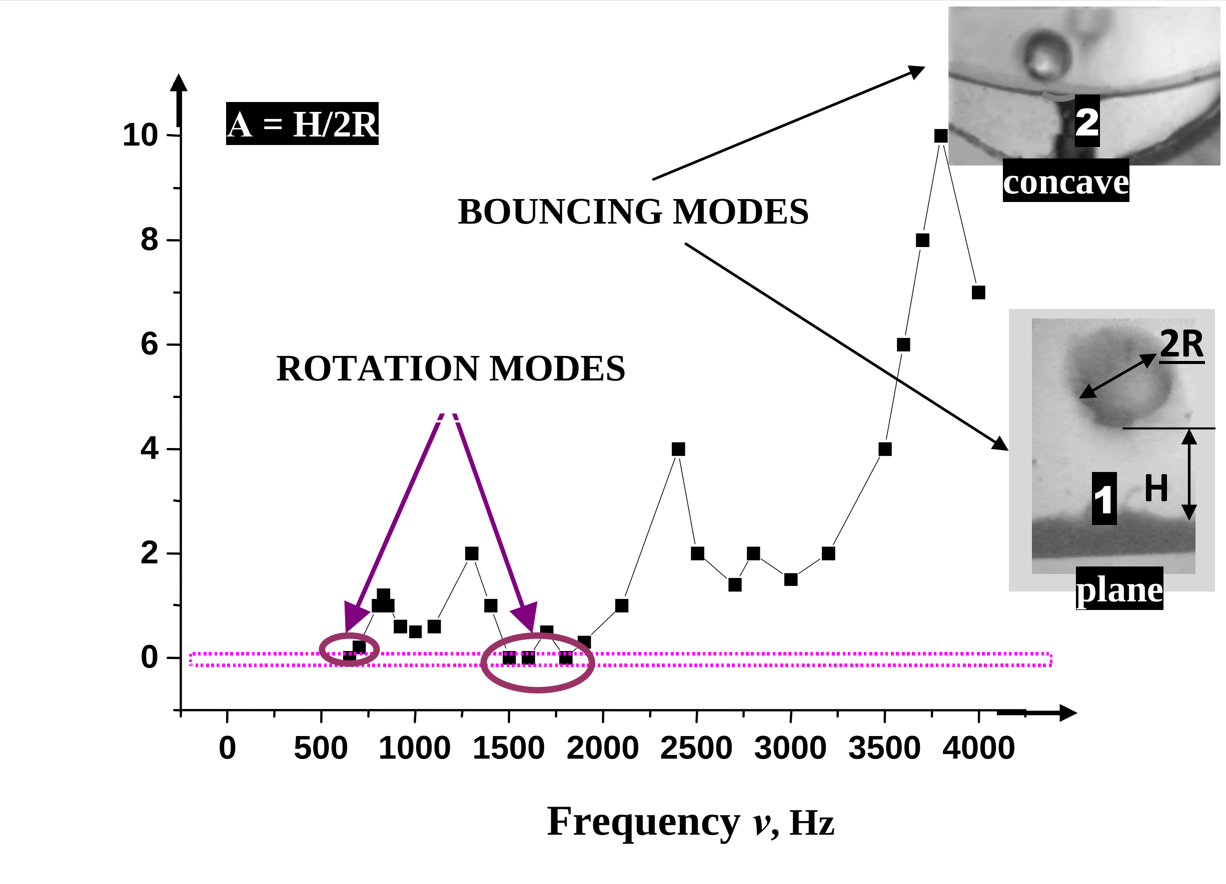
PIEZO-VIBRATOR (1):
PREPARATION FOR EXPERIMENT — SCHEMATIC DIAGRAM



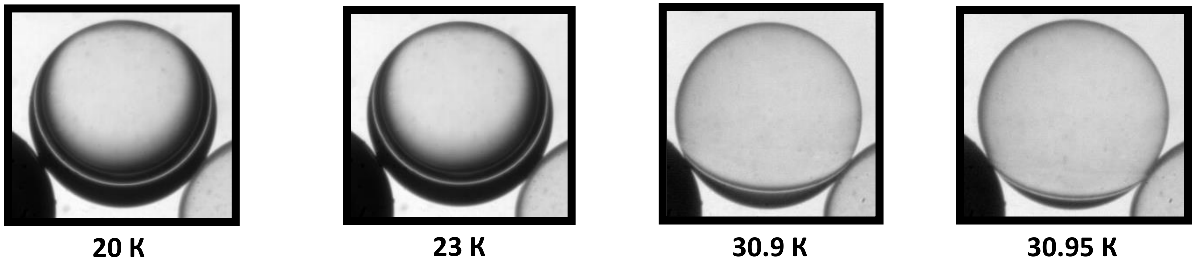
■ **Notations:**

(a) Schematic diagram of the piezo-vibrator: (a1) − experiments at T = 4.2 K, (a2) − experiments at T = 20 K;
(б) Test chamber in assembly with the piezo-vibrator: 1 − unit of target loading, 2 − test chamber;
(c) Target placement on the piezo-crystal: 3 − target, 4 − piezo-crystal.

PIEZO-VIBRATOR (2):
PREPARATION FOR EXPERIMENT — SUBSTRATE GEOMETRY



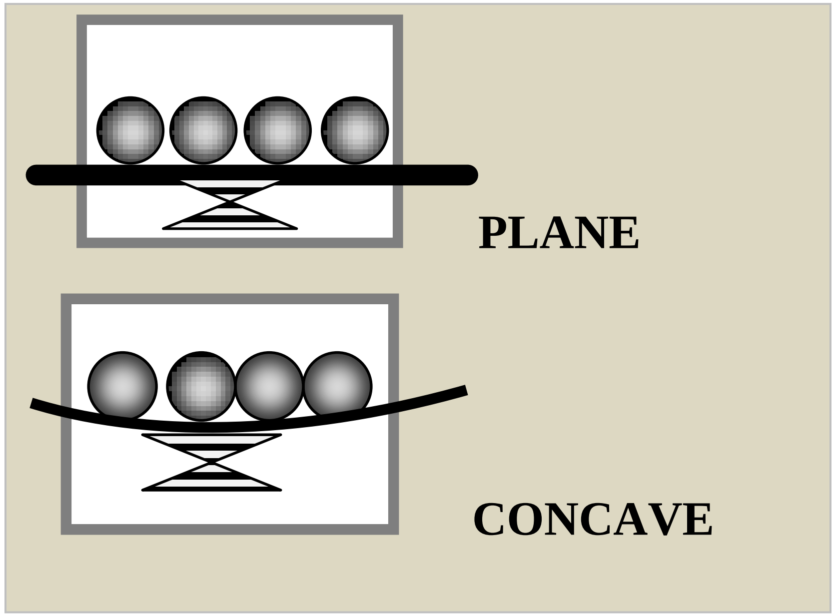
Polymer (CH) shell Ø =1 mm, fill pressure P_f = 353 atm (H_2)



Initial volume of liquid fuel depends on the initial target temperature

EXPERIMENTAL CONDITIONS:

■ Two types of substrates were used in the experiments — plane (1) and concave (2).

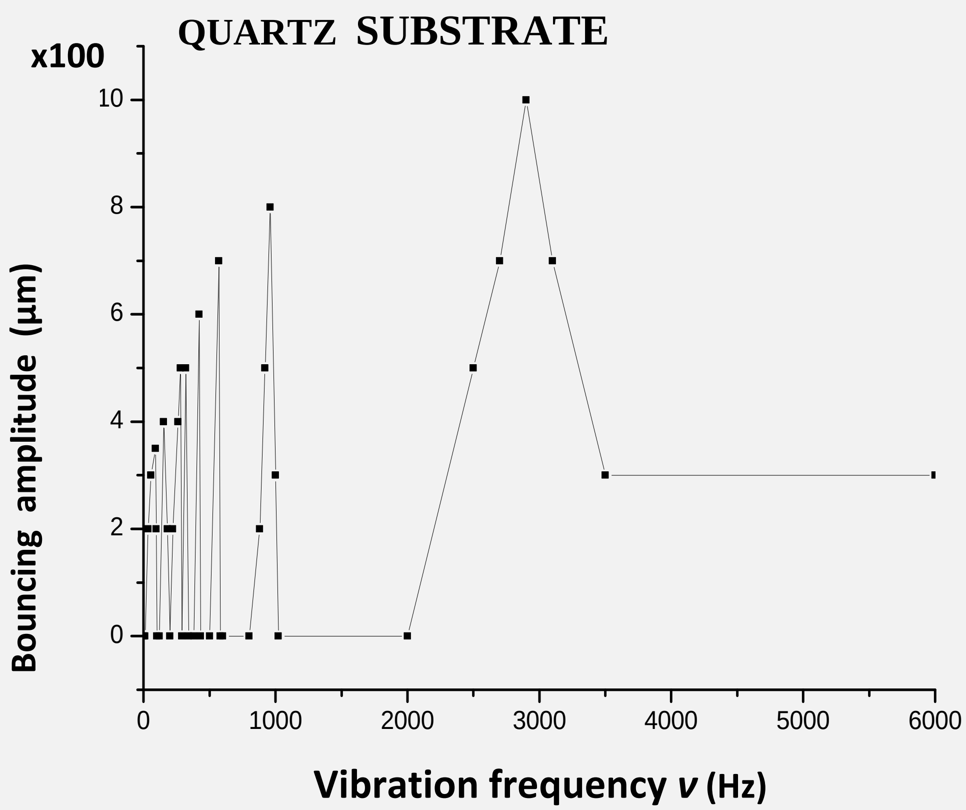


■ It is caused by the need to optimize the design of today`s piezo-vibrator.

■ The issue of using a special «substrate» in the form of quasi-closed cavity with a concave profiled surface is under examination.

PIEZO-VIBRATOR (3):

PREPARATION FOR EXPEERIMENT — TEST CHECKS



■ Shown is the dependence of *bouncing amplitude vs. vibration frequency* for the CH-shells at U = 15 V. The curve for the glass shells has a similar behavior.

Main results of the test checks

■ It was experimentally demonstrated that the bouncing amplitude for both polymer and glass shells is primarily caused by the own resonance frequencies of the piezo-substrate.

■ Conditions for increase in time (τ) of working without attaching between the target and the piezo-substrate:

— Polarity of the control pulse has no effect on τ

— Shape of the control pulse has a pronounced effect on τ → it is shown that the change from the rectangular shape to a flat pulse (saw-shaped or sine-shaped) increases the value of τ in two times.

— Type of the contact surface (dielectric or conductive):

► Quartz piezo-substrate (QPS) → τ = 30−60 sec

► Nickel-cased QPS → τ = 30 minutes

► **Inverse piezoelectric effect** *refers to a deformation of certain materials those results from the application of an electric field. The deformation could lead to either tensile or compressive strains and stresses in the material depending on the direction of the electric field.*

PIEZO-VIBRATOR (4):

PRELIMINARY MODELING RESULTS — HEAT TRANSFER DURING IMPACT

■ **Maximum contact area**

$$S_{spot-\max} = \pi\left(\frac{15mV^2R^2}{16E}\right)^{2/5}$$

■ **Time of impact**

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

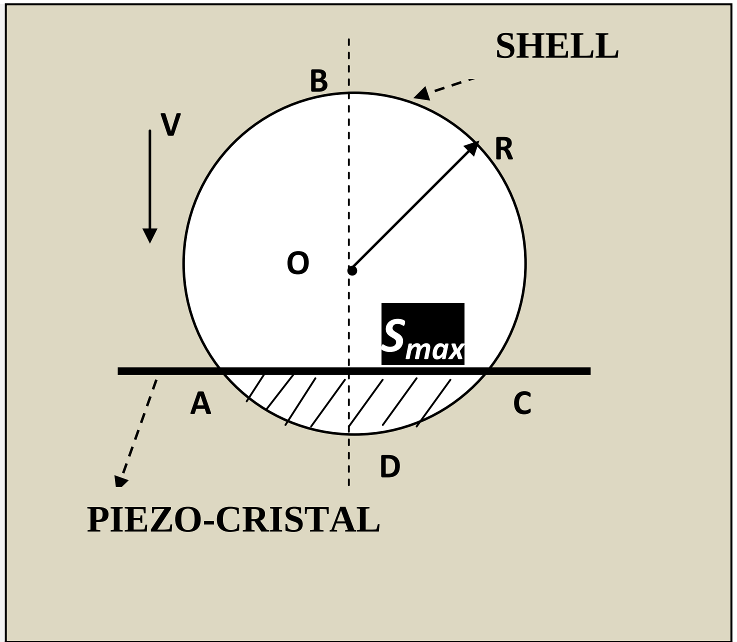
■ **Heat transfer during impact**

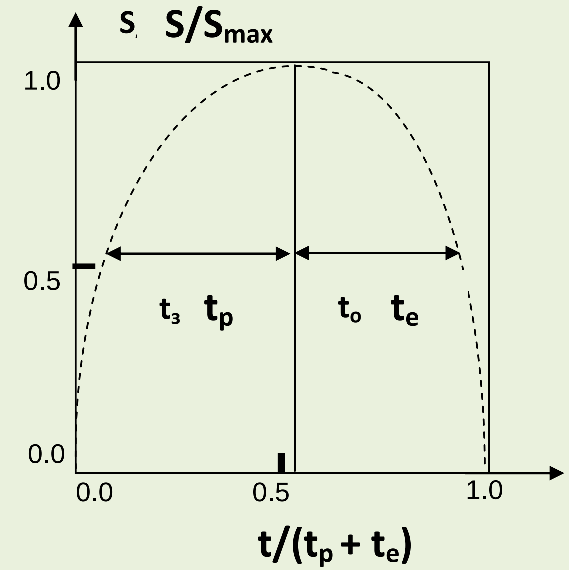
$$Q = 0.88\cdot\beta\left(T_1 - T_2\right)S_{spot-\max}\cdot t_c^{1/2},$$

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

■ **Notations:**

T — absolute temperature
R — target radius
m — target mass
V — target velocity
E — Young`s modulus of the shell
ρ — material density of the shell
C — thermal capacity of the shell
k — thermal conductivity of the shell





Change of the contact area with time

Heat exchange between worm target & cold piezo-substrate

■ **Impact is normal, i.e. we consider only the case of B-mode generation.**

■ **Impact is quasi-static, i.e. the Hertzian theory of the elastic impact is valid**

■ **During the impact the heat flow is normal to the contact area**

■ **The target temperature is slightly above the triple point T_{TP} to minimize the freezing time:**

— $T_1 \sim T_{TP}$ = 13.96K for H_2

— $T_1 \sim T_{TP}$ = 18.71K for D_2

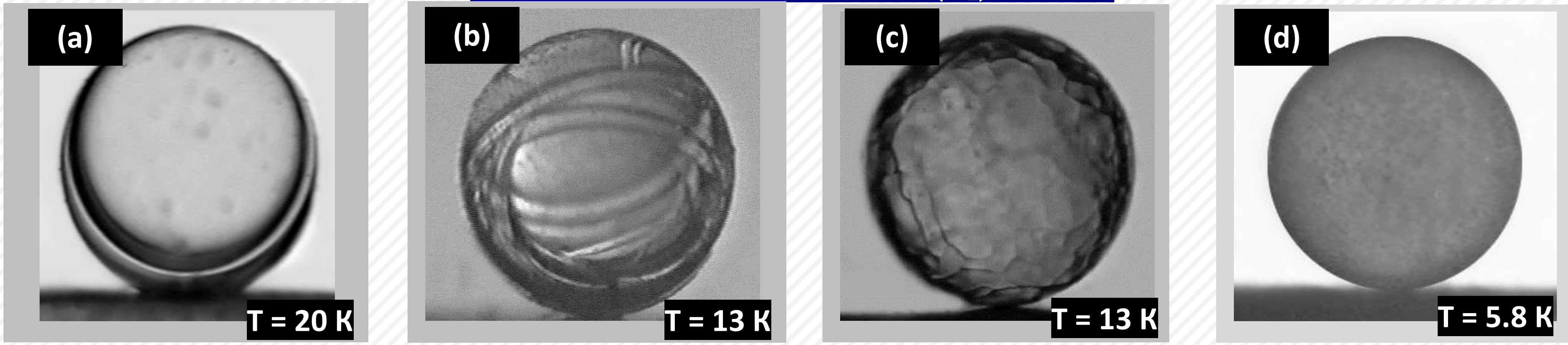
■ **The piezo-substrate has T_2 = 4.2 K**

■ **The relative amplitude A = H/2R is a parameter because experimentally it can vary from 1.5 to 10 target diameters, depending on the input signal frequency.**

■ **Here, t_e is the time of elastic rebound, and t_p is the time of plastic engagement**

SUCCESSFULL FORMATION of ultra-fine D_2 ice inside polymer shells using the cryogenic piezo-vibrator created at LPI

CH-shells ∅ ~ 1.35 mm, 350 atm (D_2) at 300 K



Initial state before target COOLING | **COOLING: no vibrations, ν = 0 (motionless target)** | **COOLING: weak vibrations, ν = 2.25 − 3.5 kHz** | **COOLING: strong vibrations, ν = 3.75 kHz**

■ **Target cooling down to T_{tp}=18.65 K (D_2) goes through a small contact area between target and piezo-substrate: the cooling rate is q = 0.1 K/s < q_{FST} = 1−50 K/s, the initial D_2 state inside the target shell is «Liquid + Vapor» (a)**

■ **It is well seen from the experiments that under vibration loading the obtained D_2-ice structures are very different:**

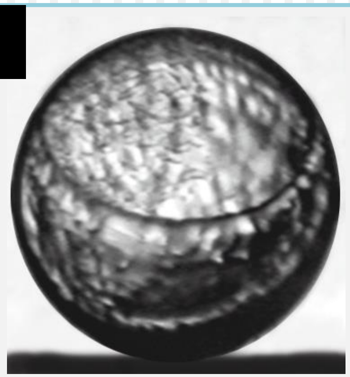
— No vibrations (ν = 0) → formation of a coarse-grained crystalline layer (b),

— Weak vibrations (A = H/R < 4) → typical crystalline structures become more smoothed due to arising of fine-grained clusters (c),

— Strong vibrations (A = H/R ~ 10) → formation of an ultra-fine D_2 ice, which quite uniformly covers the inner surface of the target shell (d).

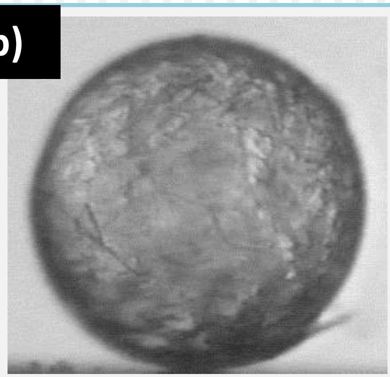
SUCCESSFULL FORMATION of ultra-fine H_2 ice inside polymer shells using the cryogenic piezo-vibrator created at LPI

(a)



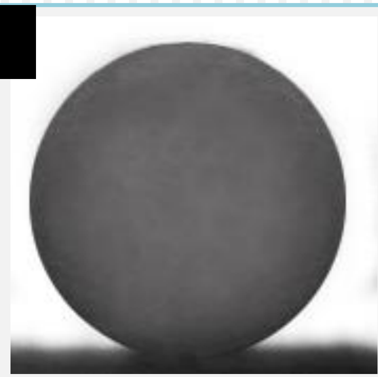
Formation of a coarse-grained crystalline layer

(b)



Layer structure becomes more smooth

(c)



Formation of an ultra-fine hydrogen layer

■ **Till now the fabrication of the cryogenic layers with an ultra-fine structure from hydrogen isotopes can be realized only at extremely high cooling rates (method FST: $q_{FST} = 1-50$ К/s).**

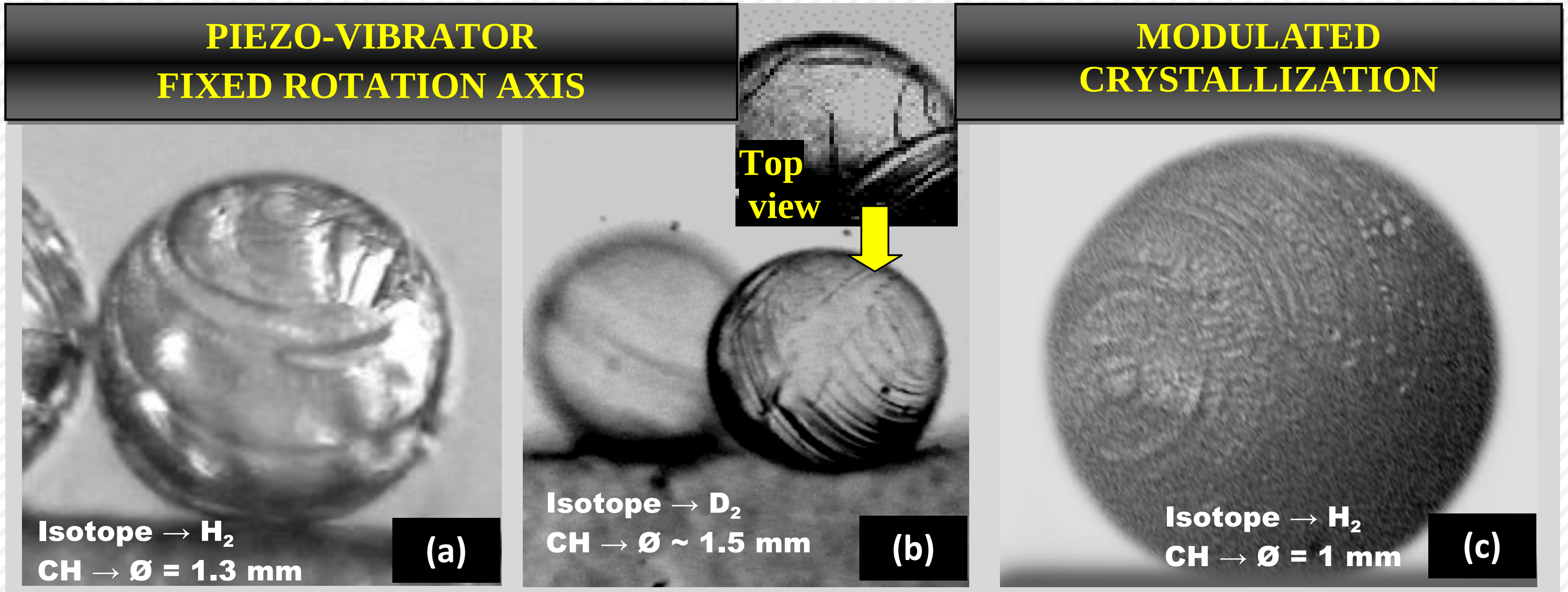
■ **The obtained results are of primary importance because they demonstrates a possibility to reduce the cooling rates with the help of vibration influence on the liquid fuel during its freezing.**

■ **EXPERIMENTAL CONDITIONS:** ► $q \sim 0.1$ К/s (a and b) and $q \sim 0.5$ К/s (c), which are less than q_{FST},
► CH- shells (∅ ~ 1.5 mm) are filled with H_2 up to 445 atm at 300 К.

■ **EXPERIMENTAL RESULTS:** (a) No vibrations ($\nu = 0$), $q = 0.1$ К/s → coarse-grained crystalline layer.
(b) At the same $q = 0.1$ К/s, but at vibration presence (2.4 kHz) the layer structure becomes more smoothed.
(c) Under synchronous rise in the level of vibrations ($\nu \sim 10$ kHz) and the cooling rate up to $q = 0.5$ К/s (but $< q_{FST}$), there is formation an ultra-fine hydrogen structure

■ **Thus, our experiments demonstrate cooling rates reducing in the conditions of high-frequency mechanical influence on the process of cryogenic layer fabrication. This makes the FST technology not only more efficient for reactor-scale targets (thick layers formation), but also more reliable and inexpensive for a laser IFE power plant.**

SPATIAL DELOCALIZATION OF THE TARGET ROTATION AXIS has a primary effect on the cryogenic layer formation with an acceptable concentricity and sphericity



► Consider a rotating spherical target moving in the piezo-vibrator. The target rotation causes a spread of liquid fuel over the inner surface of the target shell. Under certain conditions it can result in a uniform layer formation. This is just in the case of a certain «VARIABILITY» of the target rotation axis, and this «VARIABILITY» can significantly influence the layer symmetrization.

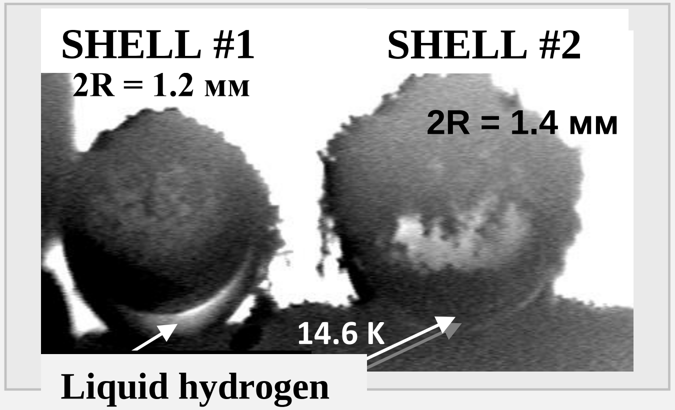
►In the opposite case of a steady-state rotation (fixed rotation axis) no layer symmetrization can be expected (a, b, c).

► At the fixed rotation axis, a MODULATED LAYER CRYSTALLIZATION is observed, i.e. a characteristic periodical allocation of the solid particles from hydrogen isotopes over the inner shell surface (a, b, c).

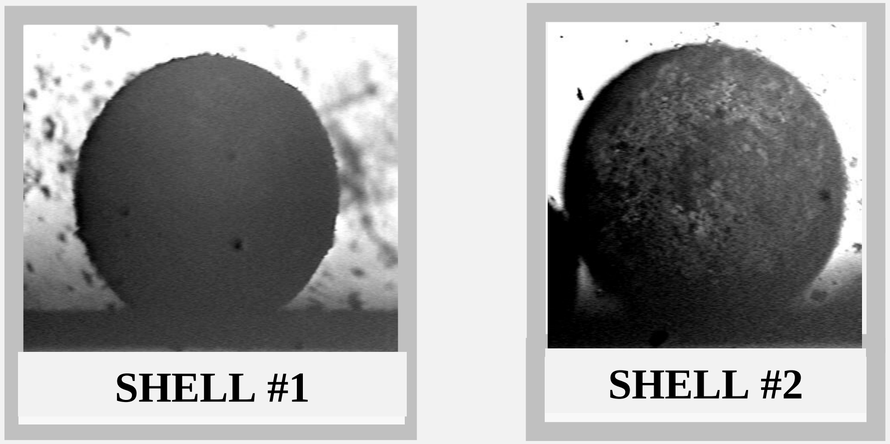
► Thus, we have found that a spatial delocalization of the target rotation axis (or in other words, random target rotation) is the necessary condition for the cryogenic layer symmetrization.

MULTIPLE TARGET PROTECTION METHODS: deposition of the outer protective cryogenic layer onto the target is another issue for study with PIEZO-VIBRATOR

(a)



Two polymer shells are inside the piezo-vibrator before the experiment.



(b)

After vibrations loading, the opaque protective layer covers the outer surface of each shell, and sufficiently uniform at that.

Exceptionally for the purposes of illustration, we set the experiment in the following way:

■ **(a) Each shell has liquid H_2 at 14.6 K, which is readily seen in the bottom of each shell. In the top part of the shells (from the outside) there is a solid deposit from the oxygen ice (T_{tp} = 54.3 K for O_2),**

■ **(б) After the piezo-vibrator operation in the bouncing mode, the solid O_2-deposit becomes redistributed sufficiently uniform onto the outer surface of each shell.**

■ **Note that in our experiments the shell at the left has a palladium coating of 150 Å thick, which is important for a double-protective layer formation:**

«METAL LAYER + CRYO LAYER»

■ **Formation of the outer protective layers «METAL LAYER + CRYO LAYER» allows to withstand the overloads during target injection at the laser focus**

SUMMARY OF THE REPORT

■ **We have discussed on a credible pathway for fabrication of isotropic ultra-fine fuel layers within ICF/IFE targets:**

— Such layers have enhanced mechanical strength and thermal stability which is of critical importance for target fabrication, acceleration and injection.

— In addition, the isotropic properties of the ultra-fine layers allows avoiding instabilities caused by grain-affected shock velocity variations.

— Finally, the isotropic ultra-fine fuel layers have a potential to advance materials for application to fusion targets fabrication in the form that meets the requirements of implosion physics.

■ **The report presents our new results obtained in this area and describes technologically elegant solutions towards creating a special layering module — cryogenic piezo-vibrator. This module is currently used to elucidate the physical fundamentals underlying the efficiency of the FST-layering method in regard to its extension on IFE requirements:**

— Consideration is being given to enhance the piezo-vibrator efficiency upon structurization of the hydrogen fuel during its layering under target exposure to the vibrations,

— Formation of the outer protective cryogenic layers to withstand the heat loads during target flight to the reactor chamber center.