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Free standing target technologies for inertial fusion energy: Target fabrication, characterization, and delivery

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Abstract

Inertial fusion energy (IFE) research indicates that the energy generation by means of cryogenic fuel target compression requires that targets must be injected to the target chamber center at a rate of about 6 Hz. This requirement can be fulfilled only if the targets are free-standing. The most interesting results concerning the activity of the Lebedev Physical Institute in the area of free-standing targets (FST) fabrication, characterization and delivery are presented.

Keywords: Inertial Fusion; Targets

1. INTRODUCTION

Inertial fusion energy is widely regarded as the energy source of the future (Hora, 2004), and intense laser and particle beams are discussed as potential drivers. The fast ignition concept is currently at the focus of the research effort (Mulser & Bauer 2004; Deutsch, 2003; Koshkarev, 2002). The current status is still dominated by intense basic research of inter action phenomena of intense laser and particle beams with ionized matter (Deutsch, 2004; Malka, 2002; Hoffmann *et al*., 1990). The availability of suitable targets was identified as a key issue for inertial fusion basic research with lasers and heavy ion beams (Callahan *et al*., 2002; Borisenko *et al*., 2003).

Target supply with repeatable target fabrication and injection is an essential technology and science component for IFE. Currently, a critically important issue of IFE is development of a free-standing target supply system to ensure fueling of a commercial power plant at a rate of several Hz (Monsler *et al*., 1995).

Technologies based on using free-standing targets (that is, FST-technologies) in each step of cryogenic target fabrication and delivery are the research area that was intensively explored at the Lebedev Physical Institute (LPI) of Russian Academy of Sciences since 1989 (Koresheva, 2000, 2003*a*, 2003*b*). The aim of these targets is to demonstrate large benefits of a layering—plus delivery scheme for a rep-rated cryogenic target fabrication (Aleksandrova *et al*., 1999*a*, 1999*b*).

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To demonstrate (on a reduced scale) the main steps of IFE target supply, a prototypical FST supply system were created at LPI (Aleksandrova *et al*., 2000*a* or *b*). The system operates with 5 to 25 free-standing targets at one time. The transport process is target injection between fundamental system elements: shell container—layering module —test chamber (see Fig. 1a) (Aleksandrova *et al*., 1996). The targets move downward along the layering channel in a rapid succession—one after another, which results in a repeatable target injection into the test chamber (see Fig. 1b). While target moving, the fuel freezes due to the heat removal through the contact area between the shell and the cold wall of the channel, and the layer summarization goes due to the target random rotation (Aleksandrova *et al*., 2002; Chtcherbakov *et al*., 2004). In essence, the test chamber is a prototypical interface unit (collector) between the layering module and injector (be it a coil gun, gas gun, or combined one) for collecting the layered targets before their delivery to the target chamber. Depending on the layering channel geometry, the target residence time inside may vary in the range of $\tau_{res} = 4–15$ s. A reduced scale operation of the FST supply system was demonstrated at a repetition rate of 0.1 Hz (see Fig. 1 and Table 1) (Aleksandrova *et al*., 2001; Koresheva, 2003*a* or *b*).

Our activity involves computer models and programs related to the FST system operation because cryogenic targets require strict control over symmetry and survival of the fuel core during transport through the chamber environment. Among them are the following:

Fuel filling: A diffusion technique is in common use for filling targets with a gas fuel. The need to minimize the

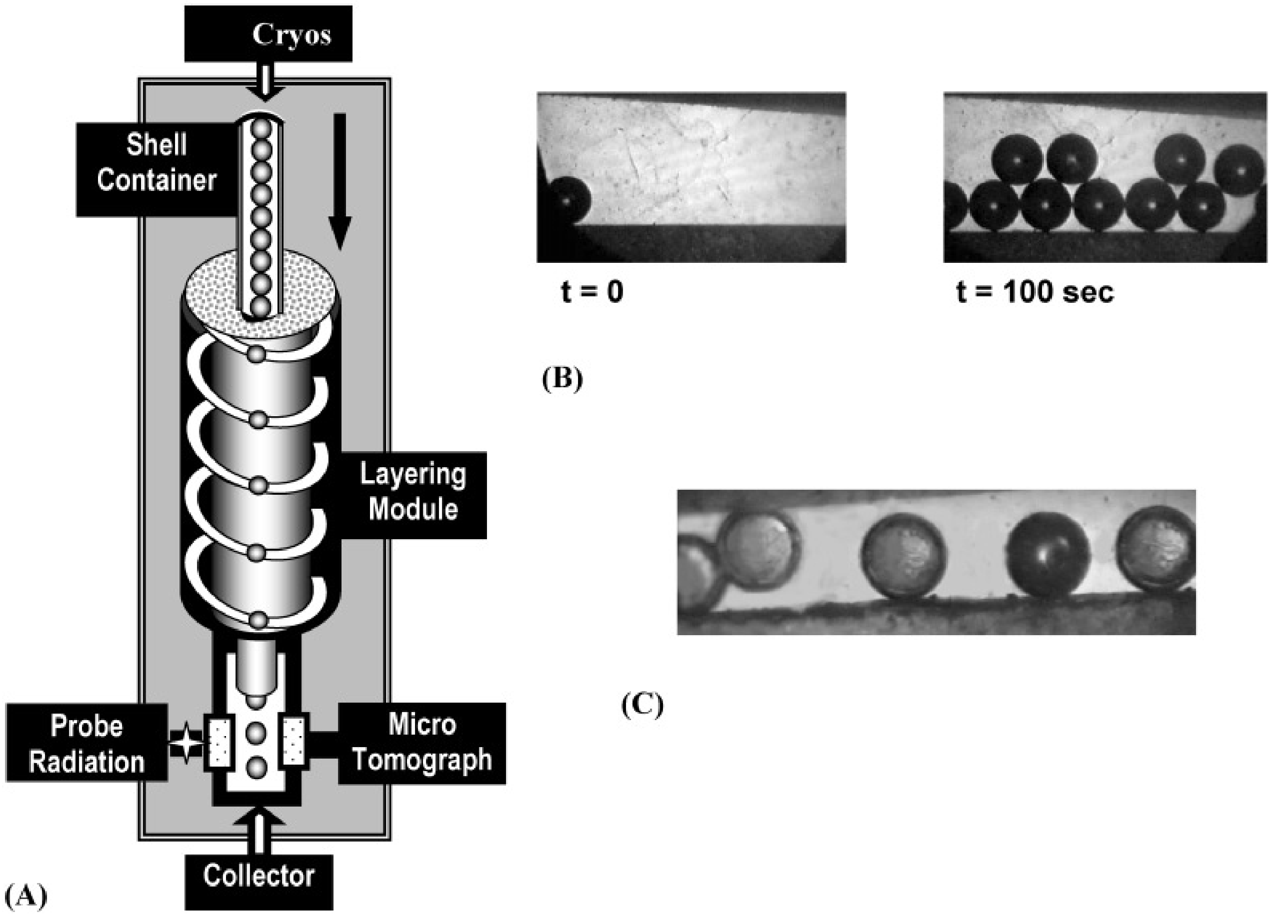

Fig. 1. Schematic of the FST system for efficient production of cryogenic targets. (**a**) FST layering module with a spiral layering channel. (**b**) Repeated target injection from the layering module to the test chamber (collector) at 4.2 K. (**c**) Cryogenic targets placed in the collector after injection: CH shells of 1 mm-dim. with a 90 μm-thick H_2 solid layer.

tritium inventory in the fill station and to decrease the radiation damage during the fill raises a question of its thorough analysis to determine an efficient pressurization scheme for single and multilayer polymer shells.

An analytical approach based on the Cauchy problem for a nonlinear parabolic equation with nonlinear boundary conditions was advanced to determine an efficient pressurization scheme for single and multi-layer polymer shells (Aleksandrova & Belolipetskiy, 1999*a*). The model nonlinearity is attributed to both the nonlinear dependency of pressure vs. gas density and the influence of material and configuration of the shell on the gas permeation. Our analysis shows that:

- The time of target filling with real gas is considerably shorter than a similar characteristic typical of perfect gas.
- For minimizing the diffusion fill time, the pressure difference taken at the outer and inner target walls to be constant with a possibly maximal value, that is, the ramp filling would be worth implementing than any other method.

The obtained results give a practical guide for design, engineering, and construction of the fill station operating both with free-standing and mounted shells (Osipov *et al.*, 1999).

Fuel layering: Fast fuel layering inside moving free-standing targets (FST) refers to a FST layering method. Physics of the fuel ice formation is based on a number of effects (Aleksandrova *et al.*, 2002). These include target cooling by heat conduction through a small contact area, elastic shell deformation during its movement in the layering module, thermal contact area expansion over the shell surface, phase transitions, and dynamic summarization of liquid fuel, etc. In order to optimize the method, an integrated FST-layering code was developed, which includes the effects important to the layering process (Chtcherbakov *et al.*, 2002). This was done numerically by solving Stephen's problem for moving boundaries between the fuel phases (gas, liquid, and solid) and for nonlinear boundary condition onto the outer shell surface.

Target characterization: *Precise characterization:* In recent years, research into the development of reliable methods and techniques for characterization and quality control of ICF/IFE targets was carried out very actively. This is

Table 1. *Performance data of the modified FST layering module*

Parameters	Performance data
Polymer shell	Demonstrated: up to 1.8 mm
Fuel material	D2 + different doping agents (0.3–16%) Demonstrated: D2 + Ne; H2 + HD; H2 + D2
Fuel layer thickness	10–100 μm Demonstrated: for millimeter size targets
Outer protective layers	
Metal reflective layer	Pd, Pt/Pd or Au (100–200 A°) Demonstrated: Pd (150 A°), Pt/Pd (200 A°)
Cryogenic solid layer	Demonstrated: cryogenic solid layer of O_2
Target production rate	Demonstrated: 0.1 Hz
Fill pressure at 300 K	Demonstrated: 100–1000 atm

motivated by the need to provide means for the precise and accurate knowledge of cryogenic target parameters. Therefore, we supplemented the FST system with a reliable diagnostic subsystem based on tomographic information processing methods (Aleksandrova *et al.*, 1999*a*, 2000*a*).

The tomographic data acquisition needed for the target reconstruction is carried out by a visual light microtomograph, which works at room and cryogenic temperatures ($T = 20$–4.2 K) (Osipov *et al.*, 2002*a* or *b*). The specially developed Target Studio software realizes the image element analysis and requires from 60 to 100 backlit images (projections) for the purpose of three-dimensional (3D) reconstruction of the cryogenic target (Nikitenko & Tolokonnikov, 2002). The principle of 3D reconstruction is as follows:

1. Obtaining a set of shadow images of a cryogenic target (or shell).
2. Defining the center for each image.
3. Measuring the bright band position with respect to the center of each image.
4. Calculation of the inner surface position of the cryogenic layer (or shell) for each image.
5. 3D reconstruction of the inner surface of the cryogenic layer (or shell) and data analysis.

Fast characterization: Methods of repeatable ultra fast target selection should inevitably be present in the research related to a future power plant. This is due to the fact that the cryogenic targets must be injected into the reactor chamber at a rate of ~6 each second (Monsler *et al.*, 1995), which is evidence of an ultrafast characterization process. This means that under target characterization the information content converges to a level of the image recognition problem. Our recent paper (Koresheva, 2004) indicates that Fourier holography methods are seen as an appropriate probe for examining the target quality in this case. We have started to work in this direction, and as a result, an algorithm based on using Fourier holograms was developed, and a corresponding simulation model was accomplished in the form of a complete computer program *HOLOGRAM* (Koresheva, 2004).

Target delivery: Cryogenic targets require strict control over symmetry and survival of the fuel core during transport through the chamber environment. Assembly of the target with a sabot shall precede the target acceleration and injection. To optimize sabot parameters, a physical model of the sabot interaction with the magnetic field of a coil was developed (Koresheva, 2003*a* or *b*; Osipov *et al.*, 2004). Relevant mathematical software *COIL* makes it possible to analyze (for different sabot materials and geometry) sabot velocity dependence on the parameter I$x\omega$. Our analysis shown that sabot made from magneto-insulator can be successfully used in injectors of any type (gas gun, coil gun, or combined ones).

At present, a part of our activity is focused on using the FST supply system to provide targets (spherical and cylindrical) and related technologies for ongoing and future target laboratory experiments. However, existing and developing target fabrication capabilities and technologies must take into account the specifics of reactor-scaled target production. Therefore, in this paper, we present the progress results of the study being done for an issue of the FST-technologies extension on IFE requirements.

2. TARGET FABRICATION

In a previous paper (Aleksandrova *et al.*, 2002), we proposed a model for rapid fuel layering inside a moving and free-standing targets. It is based on solving Stephen's problem for moving boundaries between fuel phases (gas, liquid, and solid) and for nonlinear boundary condition onto the outer shell surface. The heat transport outside the target is conduction though a small contact area. The contact area occurs due to the elastic shell deformation during target rolling along the layering channel (see Fig. 2) and can be described by a parameter $\chi = S_{ca}/S_{ts}$, where S_{ca} and S_{ts} are the surface areas of the contact and the shell, respectively. The FST layering simulation code was first developed for millimeter size targets (Chtcherbakov *et al.*, 2002). Then it was adaptable and scalable for numerical experiments with reactor ones (Chtcherbakov *et al.*, 2003; Aleksandrova *et al.*, 2003).

The starting point for our analysis is the model called a classical high gain target (CHGT). This target is a uniformly thick DT (D2) layer formed on the inner surface of a polystyrene shell (CH). We will discuss two configurations of CHGT. The first one is a 4 mm diameter CH shell with a 45 μm thick wall (Nakai & Miley, 1992). The solid layer thickness is 200 μm. In this case, our simulation code does not require any improvements. The calculations indicate

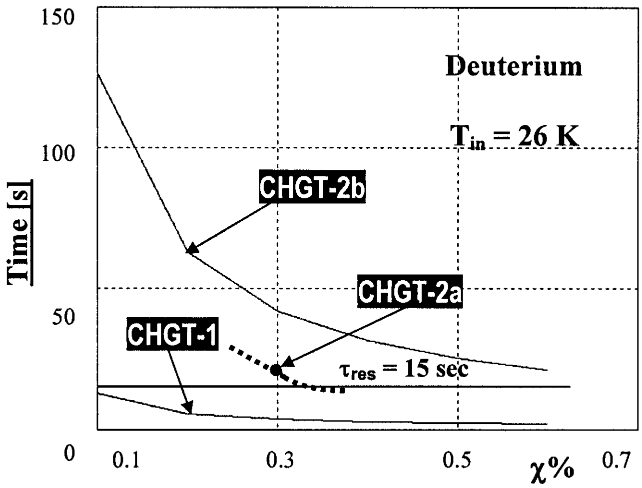

Fig. 2. The layering time *vs*. the parameter χ. The CHGT-2 configurations are as follows: (**a**) (R = 5.5 mm, ΔR = 300 μm, W = 200 μm). (**b**) (R = 6.0 mm, ΔR = 500 μm, W = 300 μm).

that the layering time is between 6 and 15 s, which depend on the layering channel geometry (Fig. 2). This means that the existing layering module (currently, τ_{res} = 4–15 s) can be used for initial experiments on reactor target formation with a configuration similar to CHGT-1.

The parameters of the other (CHGT-2) are presented in Table 2 (Monsler *et al*., 1995). Modeling the reactor targets formation, the shell properties that are of concern in the FST layering procedure are its geometry and material. The CHGT-2 is noted for its thick polystyrene shell with a relatively low thermal conductivity. This means that just the shell will define the time of fuel freezing. To carry out the calculations, we made some changes in our simulation code for the case of thick shells. The obtained results indicate that the calculated layering time is in the range of 66 and 127 s, which is considerably more than in the case of CHGT-1 (Fig. 2). This means that the existing layering module should be modified. In this regard, we created and tested a miniature device, the so-called rotating and bouncing cell (R & B cell), which is mounted at the bottom of the layering module, directly in the optical test chamber (Fig. 3) (Koresheva, 2003*a* or *b*). A vibrating membrane is an integral part of the cell. The couple "membrane & target" is driven by an input signal generated due to inverse piezoelectric effect. The R & B cell operates at cryogenic tempera-

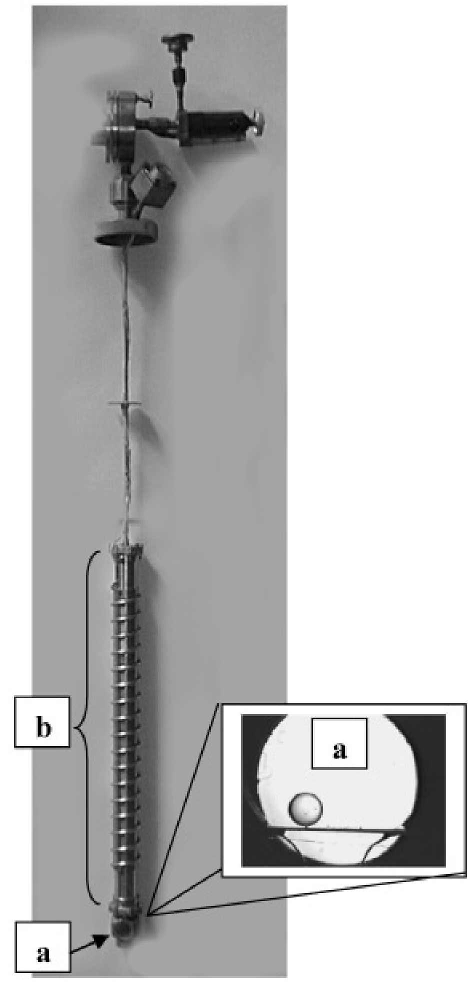

Fig. 3. In the R&B cell the layer summarization & freezing take place in a very small area as compared to the layering channel (**a**) R&B cell inside the test chamber; (**b**) spiral layering channel.

tures, which are controlled within the rates of 0.1–60 K/min. If we hold fixed temperature, it is controlled to ±0.01 K. Modulation of the input signal impresses information on the carrier frequency and amplitude. This allows placing the target in such a trajectory, which has the modes similar to those of the FST-layering channel. The advantages of the R & B cell application for fuel layering are that the time of target residence is unlimited and the device dimensions are rather small (Table 3). At the moment, our experiments have

Table 2. *The CHGT-2 parameters*

Parameters	Requirements for Dt	Estimations for D2
Polymer shell	5.5–6.0 mm	5.5–6.0 mm
Shell thickness	300–500 μm	300–500 μm
Fuel per target	2.5–5.0 mg	2.5–7.0 mg
Fuel layer thickness	200–300 μm	100–400 μm

Table 3. *Comparative characteristics of the FST-layering devices*

Simmetrization & Freezing	Dimension, mm^3	Residence time limitation
Layering channel	1500 × 25	< 1-to-15 s
R&B cell	5 × 25	Un-limited

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shown that the R & B cell application allows fabricating uniform small-grained D_2 layer on the inner surface of CH shell (Fig. 4).

For reactor targets, there is one more important issue—fuel core survival. The critical point is to withstand the environmental effects: excess heat and mechanical load arising during target delivery. Our investigations have shown that the properties of fuel material, its microstructure and composition have a dominant effect on the cryogenic layer quality and substantially determine the fuel layer response to the environment.

For example, the introduction of minor dopes (HD) to hydrogen (H2) allows the forming of cryogenic layer with glassy or super dispersed structure, which has extremely smooth surface finish (Koresheva *et al*., 2002, 2003). These experiments were carried out with more than 30 targets. It is of particular importance that the obtained glassy layer is highly stable and remains transparent upon target heating, at least within one heating cycle from 5 K to triple point of the main component and higher. This layer property has large prospects for future IFE application, because it enables the target to be injected into the reactor chamber at very low temperatures, when risk of both mechanical and thermal damage is minimal. Currently, we can form glassy layers with different doping agents and study their influence on the layer quality (Fig. 5) (Aleksandrova *et al*., 2003).

Modeling results shown (Koresheva, 2003*a* or *b*) that surface finish spoiling of crystal-line fuel layer goes quicker than that of finely dispersed layer, which follows from anisotropy in the sound wave propagation through crystal. Thus, the problem of finely dispersed and amorphous layers technology is very important in the scope of fuel core survival during the delivery process.

3. TARGET CHARACTERIZATION

The goal of ICF target characterization is to provide reliable information in a definite time. From this viewpoint, the following two stages of producing the targets are of special interest: (1) layering technique development, which requires to obtain the most complete information on the object (that is, three-dimensional (3D) reconstruction of target is necessary); (2) fueling of a commercial power plant, which requires 500,000 fusion targets each day or six fusion targets each second. In the first case, it is required to enhance information about the target configuration, whereas in the second, to shorten the characterization time (fast quality control).

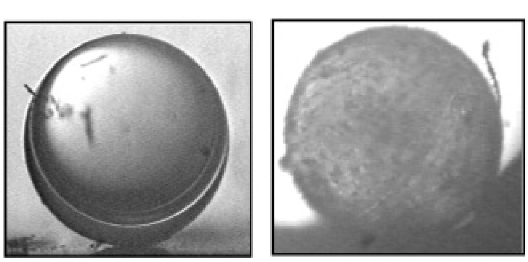
a b

Fig. 4. Cryogenic D2-layering using the R&B cell: (a) 20 K–before layering, (b) 5.8 K–after layering. Other parameters of the experiment: 1.2 mm-dim. CH shell filled with D_2 up to 300 atm at 300 K; piezocrystal–10 kHz, 75 V; layer thickness: ~47 μm; formation time: <60 s.

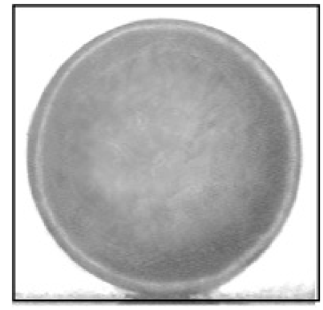

Fig. 5. Solid cryogenic layer in a glassy state. Parameters of the experiment: CH shell: 2R = 1.5 mm, coating: 200 Å Pt/Pd, 50-μm solid layer from 97%D2 + 3%Ne.

For precise and accurate characterization of individual target (microshell or cryogenic target), a prototype of the tomograph was created at LPI including a target scanning and image recorder, tomographic test chamber, and a special developed software "Target Studio" for target 3D reconstruction using a set of its backlit images obtained in visual light (Nikitenko & Tolokonnikov, 2002). The spatial resolution of the optical system is 1 μm for 490 nm wavelengths; the accuracy of target angular positioning is $\pm$1.5 to 2.5 min. The prototype operation was demonstrated in a number of controlled experiments with polystyrene microshells for a projection set ranging from 60 to 100 backlit images. The prototype has the following distinguished features: (a) operation with both free-standing and pre-mounted targets; (b) scanning of a target both at room and cryogenic (4.2 to 77 K) temperatures.

Methods for fast target characterization is also under way at LPI, namely: time minimization of all the processing stages, threshold characterization, fast characterization of a target batch, moving target characterization with simultaneous control of its quality, velocity and trajectory. One of the approaches to solve the enumerated issues is the application of the optical scheme based on Fourier holography (correlator with frequency plane). Actuating unit and photodetector only determine the operation rate of such a system (several μsec).

The operational principles of the Fourier holography scheme were analyzed and a simulation model was developed in the form of complete computer program *HOLOGRAM* (Koresheva, 2004). The shadow target images considered as amplitude transparencies enter the model input.

Our computer experiments have shown that this approach allows achieving the following results (Koresheva, 2004):

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1. recognition of the target shape perturbations in both low- and high-harmonics,
2. quality control of both a single target and a target batch,
3. simultaneous control of the flying target quality, velocity, and trajectory.

Thus, the Fourier holography scheme looks promising for fast control of IFE targets.

4. TARGET ASSEMBLY AND DELIVERY

Target delivery issues are under way at LPI, namely: target tracking and timing, target trajectory correction, technology of target protection from overloads and overheat, protecting sabot composition and geometry optimization, sabot and target assembly, etc. In this scope, the design of the device for continuous cryogenic target fabrication, target and sabot repeatable assembly, and acceleration using the coil gun was proposed (Koresheva, 2003*a* or *b*; Osipov *et al*., 2002*a* or *b*). Small changes of the design allow the repeatable assembling at cryogenic temperatures, the elements of an indirect-drive target for IFE, or cylindrical target for plasma physics experiments with heavy ion beam.

Based on the above achievements, we plan to develop a new facility for cryogenic cylindrical targets fabrication to supply the low-entropy compression experiments with heavy ion beams as a driver (Tahir *et al*., 2004; Hoffmann *et al*., 2002). The design option of the setup to supply these experiments with cylindrical cryogenic targets is shown in Figure 6.

The device consists of five main elements, namely: (1) module for cylindrical cryogenic targets fabrication and loading, (2) module for ferromagnetic sabot loading, (3) revolver for target and sabot assembly and transferring, (4) module for target and sabot extraction and splitting, and (5) module for target positioning. The physical layout of the device operation is as follows:

1. Operation of loading: cylindrical tamper and ferromagnetic sabot are placed into the revolvers of corresponding loading mechanism.
2. Cryogenic target fabrication:
   - — Loading mechanism of module 1 transfer the tamper to the output hole of the extruder.
   - — Formation of solid hydrogen cylinder using extruder and diagnostic of its parameters.
   - — Solid hydrogen cylinder loading into the tamper.

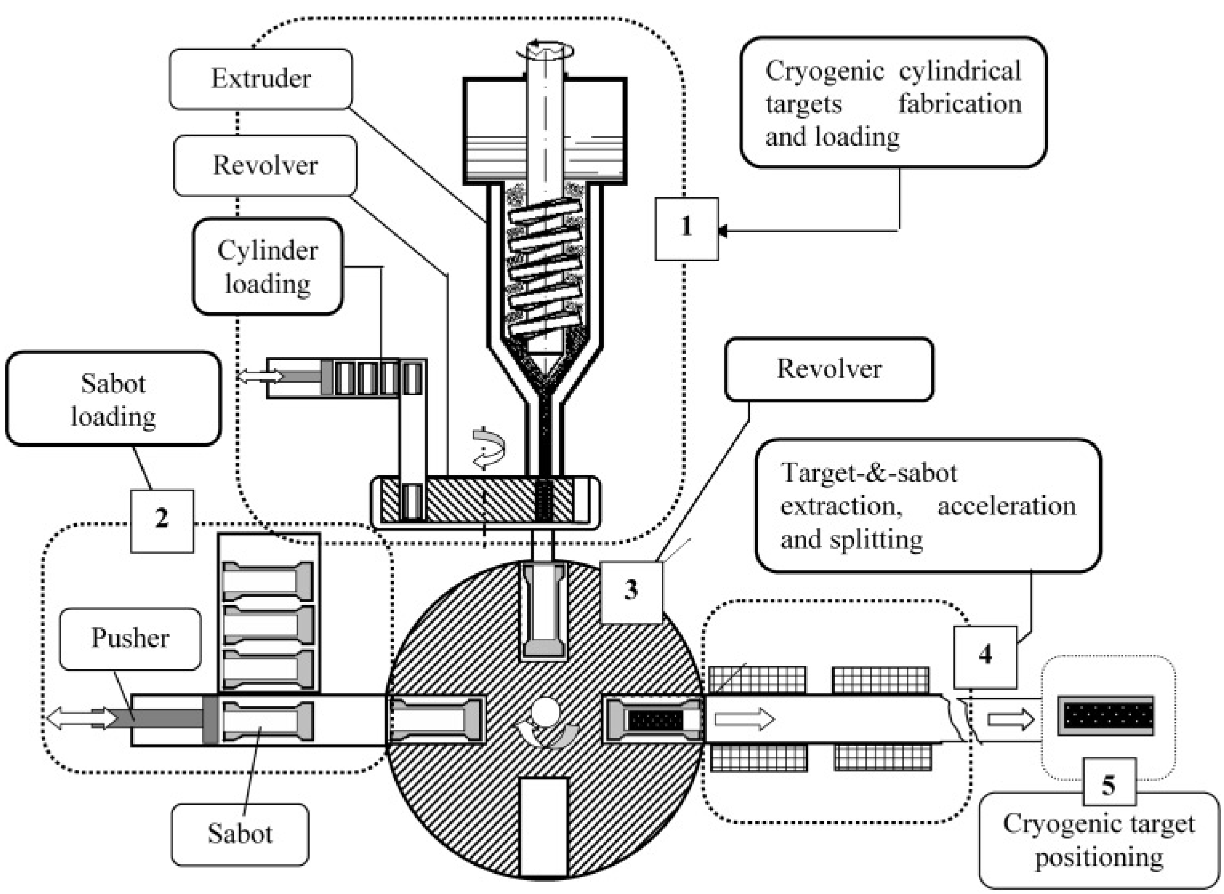

Fig. 6. A design option of the device for cylindrical targets production.

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3. Sabot and target assembly:
   — Revolver turn for transferring the sabot to the output of module 1.
   — Cryogenic target loading into the sabot, which is placed inside revolver of module 3.
   — Revolver turn for transferring the target and sabot assembly to the input of electromagnetic injector.
4. Electromagnetic extraction of target and sabot assembly.
5. Sabot and target splitting (not shown on Fig. 6).
6. Target delivery to the experimental chamber.
7. Target positioning at the chamber center.

There are two options for consideration concerning target delivery and positioning, namely: (a) pre-mounted target manipulating, and (b) injection. In the last case, the setup will be capable of operating in both single-step and rep-rate modes of target production and delivery. We plan to create a small-scaled experimental facility, which make it possible to put this activity into practice.

Theoretical and experimental study was carried out, which first confirm the possibility of the ferromagnetic sabot acceleration in a single coil at cryogenic temperatures (Fig. 7). Further analysis has shown that application of magneto dielectric instead of ferromagnetic makes it possible to reduce the sabot weight in 3 to 4 times with retention of its magneto active properties, which allows to accelerate effectively the sabot both in a coil and gas gun as well as in the coil and gas hybrid injector (Osipov *et al*., 2002*a* or *b*). A physical model of acceleration of the magneto dielectric sabot in the electromagnetic field of solenoid was created and relevant mathematical software *COIL* was developed, which allowed optimization of sabot composition and geometry.

Deposition of the outer ablating onto the target is another issue for our study. The ablating layer can be used for (a) protecting target during its flight inside reactor chamber and (b) controlling the target flight trajectory. Initial work was done to develop the physical layout of such target formation.

Using the R & B cell, we first demonstrated a process of deposition of the dispersed layer from solid oxygen onto the outer surface of the polystyrene shells (Fig. 8) (Koresheva, 2003; Aleksandrova *et al*., 2003). Allowing for the obtained results (opaque protective layer), we propose the following physical layout of the target formation: fuel filling, fuel layer formation, target characterization, and if the target is within the specifications, deposition of the outer ablating layer.

5. 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. In this paper we have presented our new results obtained in this area and described technologically elegant solutions towards demonstrating a credible pathway for mass production of IFE cryogenic targets.

Analyses of calculations and operating system parameters shown that we can identify key issues which require future study for each type of classical high gain targets, and start the experiments on IFE target technology development based on FST technologies.

The most promising options for further research and development in the area of IFE fabrication are as follows: (a) application of the R & B cell for fuel layering as well as for outer ablating layer creation, (b) formation of a fuel layer in a "glassy" state using minor doping, (c) target precise characterization using a 100-projections tomograph, (d) target fast characterization using the Fourier holography approach, (e) cryogenic assembly of the elements of indirect-

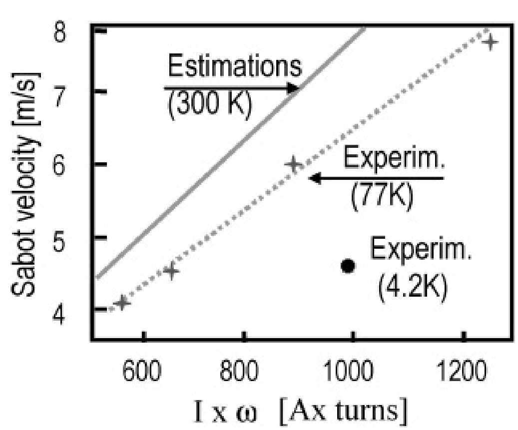

Fig. 7. Ferromagnetic sabot acceleration in a single coil.

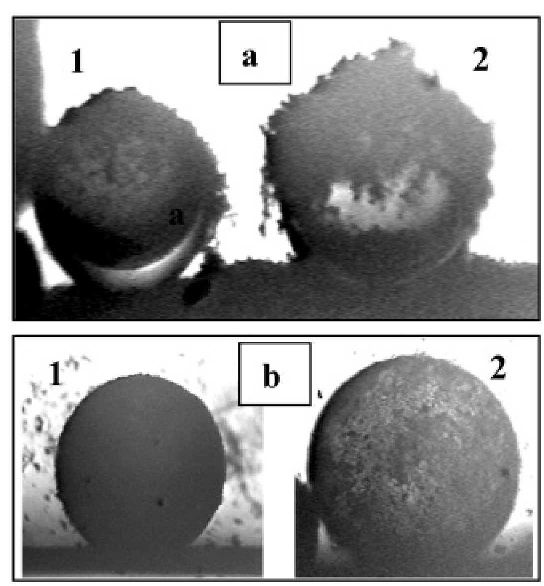

Fig. 8. Deposition of the outer protective cryogenic layer onto the target using the R&B cell (T = 14.6 K). (**a**) CH shells inside the R&B cell prior to the experiment. Shell 1 (∅1.2 mm) has a palladium coating of 150 Å thick; Shell 2: ∅1.4 mm; (**b**) An opaque protective cryogenic layer covers each shell after the R&B cell operation in the mode of target bouncing.

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drive target, cylindrical target and/or target assembly with protecting sabot (single-step and repeatable modes). We plan to create a small-scaled experimental facility, which make it possible to put this activity into practice.

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