Study on fabrication and manipulation of HEDgeHOB cryogenic targets

E.Koresheva 1), I.Aleksandrova 1), E.Koshelev 1), A.Nikitenko 1), T.Timasheva 1), S.Tolokonnikov 1), A.Belolipetskiy 2), V.Kapralov 3), V.Sergeev 3), A.Blazevic 4), K.Weyrich 4), D.Varentsov 4), N.A.Tahir 4), S.Udrea 5), D.H.H.Hoffmann 5)

1) P.N.Lebedev Physical Institute of RAS, Moscow, Russia
2) A.A.Dorodnitsin Computing Centre of RAS, Moscow, Russia
3) St.Petersburg State Polytechnical University, St.Petersburg, Russia
4) Gesellschaft für Schwerionenforschung mbH, Darmstadt, Germany
5) Technische Universität Darmstadt, Darmstadt, Germany

e-mail contact of main author: koresh@sci.lebedev.ru

Abstract. The paper addresses the issue of a specialized cryogenic system (SCS) creation for carrying out the experiments in the field of **H**igh **E**nergy **D**ensity matter **ge**nerated by **h**eavy i**o**n **b**eams (HEDgeHOB). Theoretical and experimental studies have been performed in the following directions: target fabrication, target manipulation, and target survival. As a result, a reliable way for the SCS creation has been proposed.

1. Introduction

HEDgeHOB collaboration plans to carry out a set of experimental researches in the field of high energy density matter generated by the interaction of intense heavy ion beams. One line of the researches was named LAPLAS (Laboratory PLAnetary Science) [1,2]. This scheme proposes low-entropy compression of a material like frozen hydrogen or deuterium ice that is enclosed in a cylindrical shell of a high-Z material like gold or lead. A schematic of the HEDgeHOB cylindrical cryogenic target for LAPLAS experiment is shown in Fig.1.

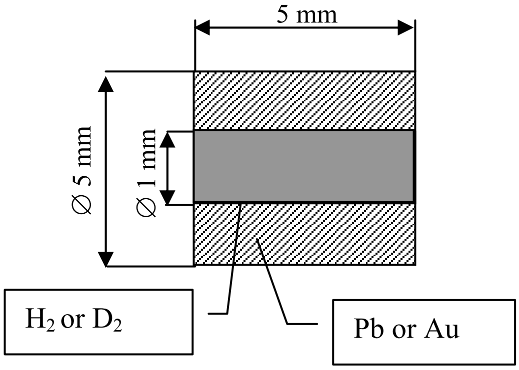

FIG.1. Schematic of HEDgeHOB cryogenic target

For carrying out the LAPLAS experiments, a key problem is creation of SCS intended for fabrication, delivery and positioning of cylindrical cryogenic targets in the center of the experimental chamber without target degrading [3]. The results of theoretical and experimental studies on these problems are discussed below.

2. Study on target fabrication and delivery

Note that one of the main requirements to the SCS is that the LAPLAS experiment must be supplied with cryogenic targets with a rate of $\geq$ 1 target per hour [2]. That is why practically all the elements must be constructed in such a way as to realize the SCS operation with free-standing targets (FST approach [4]). A basic advantage of such approach is minimization of time and space scales of all working operations that ensures the possibility of (a) rapid target transport between SCS modules, and (b) continuous operation of SCS with a given rate of target delivery. Besides, the FST approach has much promise under using the DT-mixture as a fuel core.

Before the SCS designing, much development work has been made:

1.Fabrication study. For cryogenic core creation two existing methods are considered as the most promising. These are the *in-situ* method [5] and solid extrusion method (solid H_2

or D_2 extruding through a special nozzle) [6-8]. The optimal temperature of cryogenic core fabrication in both methods constitutes 10-11 K. As for a cylindrical shell from the lead or gold, our study has shown that to create such shell the most promising method is the mold pressing (Fig.2). Target characterization will be done by optical method [9] just after cryogenic core fabrication and just before target irradiation.

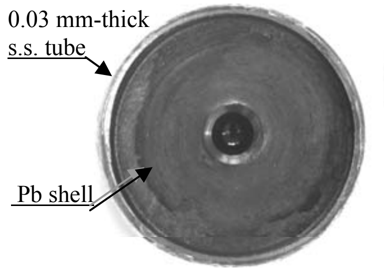

FIG.2. Lead shell of HEDgeHOB cryogenic target made by mold pressing. The shell is placed inside thin s.s.tube

2. Manipulation study, which includes two principle stages:

- *Target delivery*. Free-standing target must be transported along the guiding tubes (gravitationally or electromagnetically) to the chamber center. As lead is a very soft material, the shell must be inside a special protective capsule during the delivery stage. Our experiments have shown that a thin stainless steel tube (gravitational delivery) or ferromagnetic sabot (electromagnetic delivery) can be successfully used for target surface protection. A final delivery moment is fixing of a free-standing cryogenic target onto a holder. Experimentally (see sec.3), a reliable fixing can be achieved by using a special groove created in the holder (Fig.3).

- *Target positioning* at the chamber center relatively the irradiation beam axis. This stage is characterized by degrading effect of radiation heat transfer from the hot chamber wall (T=300K) to the cylindrical cryogenic target (T=10-11 K) as well as of contact heat-exchange between the target and the holder. The optimal choice of the experimental conditions at which the target does not loose its quality is one of the most important tasks while creating the SCS. Thus, we must solve not only the problems of target fabrication and manipulation but also the problems of target quality survival during target delivery and positioning. A thorough analysis of this problem will be given below.

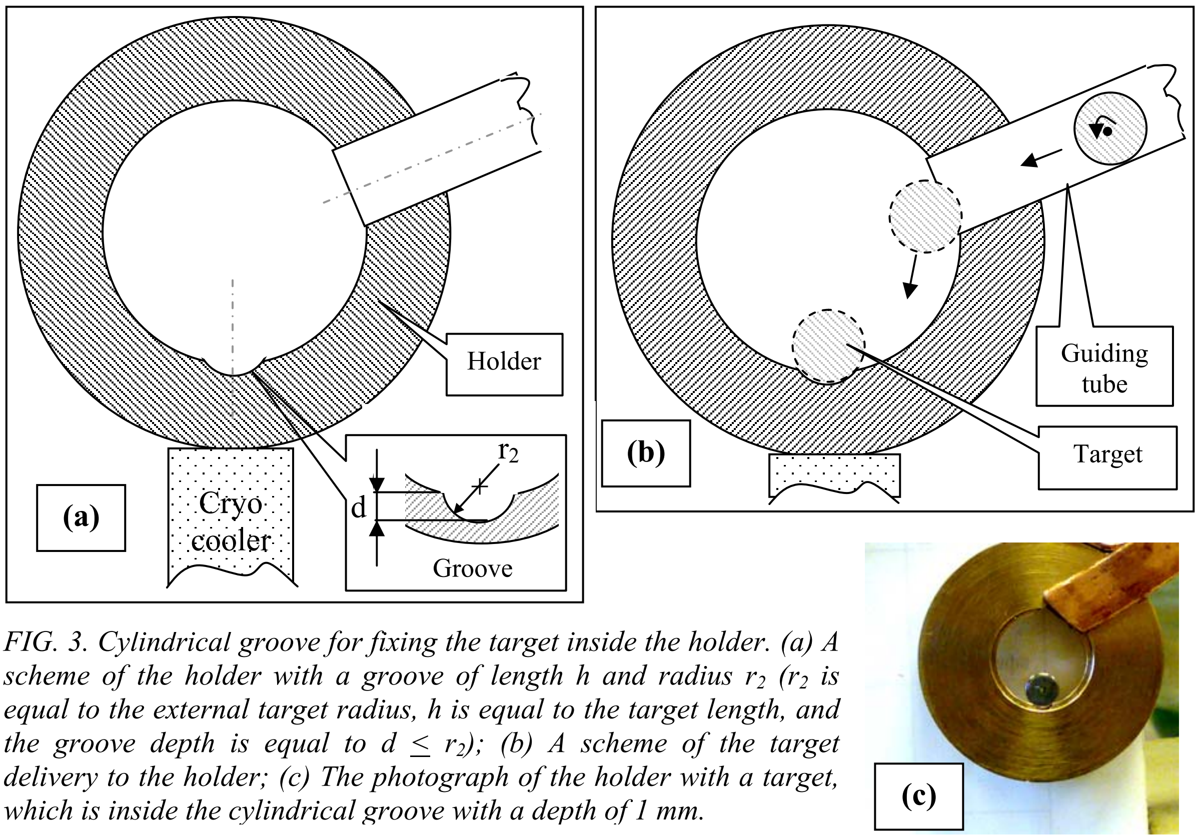

FIG. 3. Cylindrical groove for fixing the target inside the holder. (a) A scheme of the holder with a groove of length h and radius r_2 (r_2 is equal to the external target radius, h is equal to the target length, and the groove depth is equal to $d \leq r_2$); (b) A scheme of the target delivery to the holder; (c) The photograph of the holder with a target, which is inside the cylindrical groove with a depth of 1 mm.

3. Target survival study

In this section, there are analyzed the processes of cryogenic target destruction, and there are given the recommendations that allow to avoid the target quality degrading. Radiation heat transfer from the hot wall to the target can result in the cryogenic core heating above the triple point of the fuel matter, which, in turn, results in fuel melting and flowing out from the inner cavity of the cylindrical target shell. We start the study of this process from the following moment. The cylindrical cryogenic target (optimal temperature 10-11 K) is placed in the groove (Fig.3(b,c)) of the holder, and the holder temperature should be determined. The holder with the target is placed at the center of a vacuum chamber with hot walls, and the walls temperature is 300 K.

An initial estimation of the characteristic time of thermal processes can be obtained from a study based on using the Fourier number as a simulation criterion of the nonstationary thermal processes. The Fourier number (F) characterizes the correlation between the rate of thermal conditions change in the environment and the rate of temperature field transformation inside the analyzed system (it is a cryogenic target in our case). The Fourier number depends on the characteristic system dimension and the thermal diffusivity coefficient:

$$F = \frac{a \cdot \tau}{l^2} \tag{1}$$

where l – characteristic linear dimension of the system, τ - characteristic time of external conditions change, $a=\lambda/(C\rho)$ – thermal diffusivity coefficient, λ - thermal conductivity coefficient, ρ - density, C – specific thermal capacity.

The parameter $\tau = l^2/a$ may be considered as a quite characteristic time for the thermal processes analyzed in our study [10]. There were made calculations of the characteristic times τ for the cryogenic target with the following linear dimensions: 2.1 mm – wall thickness of the metal shell, and 0.4 mm – solid-hydrogen core radius. The thermal physic properties of the materials used in the calculations are taken from [11], and the results of calculations are shown in Tables 1 and 2.

TABLE 1: CHARACTERISTIC TIMES OF THERMAL PROCESSES FOR Au & Pb, SEC

T °K	Pb	Au
4	1,08298E-4	9,10481E-6
5	2,62740E-4	1,5082E-5
6	5,24652E-4	1,98955E-5
7	6,91719E-4	3,37863E-5
8	1,32000E-3	4,73738E-5

TABLE 2: CHARACTERISTIC TIMES OF THERMAL PROCESSES FOR H2 ISOTOPES, SEC

T °K	D	n-H2
4	0,01004	0,09794
5	0,00625	0,03769
6	0,00542	0,02172
7	0,00627	0,01909
8	0,00685	0,01716
9	0,01173	0,02032
10	0,01778	0,02365
11	0,02872	0,02965
12	0,04387	0,03577
13	0,06046	0,07901
14	0,08261	
15	0,11389	
16	0,15647	
17	0,20887	
18	0,2802	

It is obvious that thermal processes in gold are the most rapid ones. The thermal processes in the hydrogen isotopes are slower than in metals (Au, Pb). This means that the time estimations obtained for the metal shell are of «lower estimate», i.e., the process of fuel heating is not quicker than the process of shell heating.

Taking into account the above, let us estimate the rate of cylindrical shell heating. In general, the thermal conductivity equation without any internal sources is:

$$\frac{\partial}{\partial t}(c \cdot \rho \cdot T) = div(\lambda \cdot gradT) \tag{2}$$

Volume - integrated equation (2) has the form

$$\iiint_V \frac{\partial}{\partial t}(c \cdot \rho \cdot T)dv = \iiint_V div(\lambda \cdot gradT)dv \tag{3}$$

Then, using the Gauss-Ostrogradskij theorem (or divergence theorem) we obtain

$$\iiint_V div(\lambda \cdot gradT)dv = \cdot \iint_S \lambda \cdot gradT \cdot \overrightarrow{ds} \,. \qquad (4)$$

According to the Fourier formula we have the relation for the heat flux Q

$$Q = -\lambda \cdot gradT \,,$$

and, as a consequence, equation

$$\frac{dT}{dt} = \frac{S}{V} \cdot \frac{1}{c \cdot \rho} \cdot Q \,, \qquad (5)$$

where S is the cylinder surface area, V is the cylinder volume, c *and* ρ – are thermal capacity and density of the shell material. If heat input to the target is caused by only thermal radiation from the hot chamber wall then equation (5) is of the form

$$\frac{dT}{dt} = \frac{S}{V} \cdot \frac{1}{c \cdot \rho} \cdot \sigma \cdot (\alpha \cdot T_c^4 - \beta \cdot T^4) \qquad (6)$$

where α is the absorption coefficient, β is the emissivity factor, σ is the Stefan-Boltzmann constant, T_c is the chamber wall temperature. Since in our case the target temperature is considerably lower than the chamber wall temperature, equation (6) can be written in the form:

$$\frac{dT}{dt} = \frac{S}{V} \cdot \frac{1}{c \cdot \rho} \cdot \alpha \cdot \sigma \cdot T_c^4 \qquad (7)$$

Let us suppose now that some part of the cylindrical shell with a relative square S_t has the temperature $T_{o.}$ This means that while the target is heated due to the thermal radiation, there is generated an additional heat flux, which for the cylindrical target has the following form [12]:

$$Q = 2 \cdot \pi \cdot \lambda \cdot h \cdot (T_0 - T) / \ln(r_2/r_1) \qquad (8)$$

In this case equation (7) takes the form:

$$\frac{dT}{dt} = \frac{S}{V \cdot c \cdot \rho} \cdot \left((1 - S_t) \cdot \alpha \cdot \sigma \cdot T_c^4 + \gamma \cdot \lambda \cdot S_t \cdot \frac{(T_0 - T)}{r_2 \ln\left(\frac{r_2}{r_1}\right)} \right) \qquad (9)$$

where γ is the coefficient taking into account a degree of the heat contact imperfection (at ideal heat contact γ=1), h is the cylinder length, r_1 is the internal cylinder radius, r_2 is the external cylinder radius.

Let us note that the coefficient γ characterizes the value of the contact thermal resistance and depends on many factors such as the surface finish class of contacting bodies, the presence of oxide or adsorbed film on them, the initial temperature difference of the contacting bodies and other experimental conditions. Since the exact value of coefficient γ can be found only experimentally, in the calculations made below the value γ is varied in a wide range of values (from 1 to 0.01).

There was created software (SW) to calculate the process of cylindrical target heating (equations (7)-(9)). The calculation can be made for different geometrical parameters of the shells made of lead or gold. Thermal physic properties of these materials are given in [11].

Using the created SW there were made calculations of heating the lead and gold cylindrical shells with the following parameters: external radius 2.5 mm, length 5 mm, internal radius 0.4 mm. The initial shell temperature T_i= 4.2 K, which corresponds to the minimally possible target temperature. The results of calculations have shown that in the case of radiation heating only (equation (7), T_C = 300 K) the lead shell is heated from 4.2 K to 14 K (recall that at T=13.96 K H_2 begins to melt) for ≈ 30 sec, and the gold shell – for ≈12 sec. This is pressed for time to realize the process of target manipulation in the delivery and positioning stages.

Note also that the LAPLAS experiments require the target, which is placed onto a special holder of the positioning device. This means that besides the heat exchange caused by radiation (between the cold target and the hot chamber wall), there appears an additional (contact) heat exchange between the target and the holder. Let us also take into account the fact that from the moment of target arrival at the holder and till the moment of its irradiation by intense heavy ion beams, one need not only to perform an exact target positioning relative to the radiation axis but also to control the quality of the cryogenic core and the target faces (final control). Of course, all the manipulations with targets must be within a certain margin of hours. If the holder is at room temperature, then the time interval is less than 1 sec (equation (9)). This means that it is necessary to reduce the thermal target loads at the expense of developing the special protective measures. Application of a cryogenic holder is a way to meet the goal.

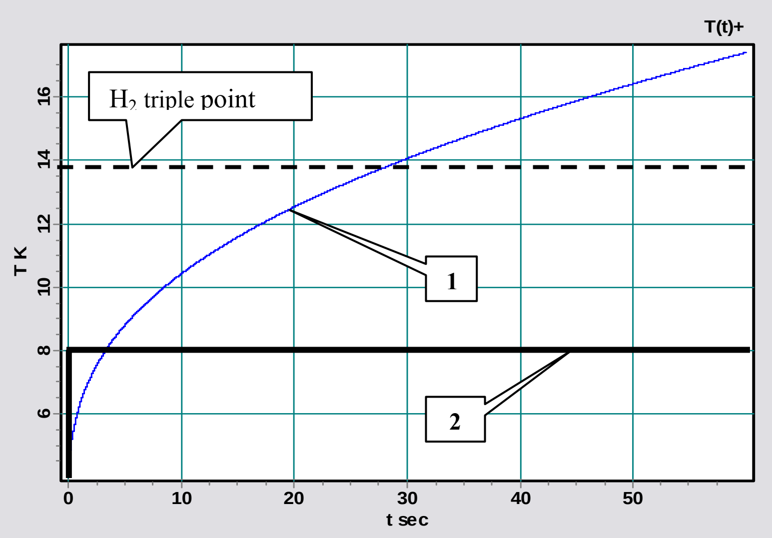

FIG.4. Calculation results of the lead shell heating due to the chamber wall radiation in the absence (1) and in the presence of the cryogenic holder (2). The calculation parameters: chamber wall temperature is T_C =300 K, holder temperature is T_0 = 8 K, initial temperature of target is T_i=4.2 K

As mentioned above, a reliable target fixing, which provides stability of the target position and the maximal contact between the target and the holder, is a cylindrical groove with a length equal to the target one (h) and with a radius r equal to the external target radius ($r=r_2$). By changing the groove depth d (see Fig.3,a), we can change the contact area from S_t=50% ($d=r_2$) and lower. The performed tests have shown that the target is stably fixing in the cylindrical groove with a minimal depth d=1 mm (S_t=19%; Fig 3, c).

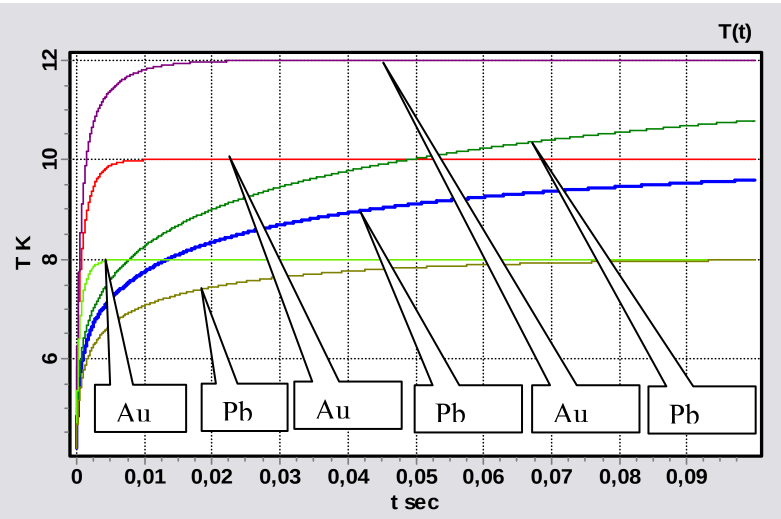

FIG.5. Heating of the cylindrical shell placed inside the chamber onto the cryogenic holder. The calculation parameters: Pb or Au cylindrical shell, diameter is 5 mm, length is 5 mm, thickness is 2.1 mm; T_C = 300K, α = 10%; T_0= 8 K, 9 K, 10 K, 11 K, 12 K; γ =50%, S_t = 10% , T_i =4.2K

Fig.4 shows the calculation results of the lead shell heating caused by thermal radiation of the chamber wall (T_c = 300 K) in the absence and in the presence of the shell contact with a cold substrate (cryogenic holder). As seen from the calculations, the lead shell (initial target temperature 4.2 K) reaches the holder temperature (8 K) for the time less than 50 msec, and whereupon, the shell temperature does not change.

Fig.5 shows the lead and gold shell temperatures versus time at different holder tempperatures. The shell is inside the vacuum chamber with a wall temperature of T_c = 300 K. The holder temperature varies from 8 K to 12 K. The initial target temperature is equal to 4.2 K. All calculated curves have a similar form – for a relatively short time the target temperature reaches the "saturation" temperature T_H, which insignificantly exceeds the holder temperature T_0 and practically does not rise later. It is rather easy to estimate the value of this temperature using equation (9), in which we will set the time derivative equal to zero (i.e., the left side of equation):

$$T_H = T_0 + \frac{\alpha\sigma T_c^4}{\gamma\lambda} \cdot r_2 \ln\frac{r_2}{r_1} \cdot \frac{(1-S_t)}{S_t}. \qquad (10)$$

Table 3 shows typical times of the temperature balance settling between the lead shell (initial temperature $T_i = 4.2K$) and holder for the conditions indicated in caption for Fig.5. Here t_H is the time of reaching T_H. In the above calculation, the initial temperature of the lead shell T_i was equal to the minimally possible target temperature T_i = 4.2 K. This means that there must be added in scenario of the target fabrication and delivery one additional stage related to the shell cooling. Besides, the outer surface of the elements of the target delivery system (delivery from the fabrication module to the cryogenic holder) must be also cooled to the temperature of 4.2 K, and this will require a considerable consumption of the liquid helium – one of the most expensive components.

As an alternative, we consider the case when the value T_i is close to the temperature at which the target was prepared in the fabrication module. Both for the extrusion and *in situ* methods the optimal temperature is 10 – 11 K. Therefore, in the next series of calculations we will take the initial temperature of the lead shell equal to T_i =11K. Let us note also that the target is stably placed on the holder if the value of the relative contact area is in the range of S_t = 20 – 50 % (it has been found experimentally). Let us take the minimum value S_t = 20%. According to the technical requirements the target temperature T_{CT} at the moment of its irradiation must not exceed the triple point temperature T_{tp} for the corresponding fuel isotope. Its minimum value is $\sim$ 4.2 K. Then, in the case of cryogenic hydrogen core we have the following temperature range: $T_{tp}=13.96K > T_{CT} \geq 4.2\ K$, and in the case of deuterium core: $T_{tp}=18.65K > T_{CT} \geq 4.2\ K$. Taking into account all stated above, we determine the cryogenic holder temperature as equal to T_0 = 5, 8, 10, 13, 18 K. The coefficient γ is equal to 50%

The obtained results testify that even at T_i = 11 K the lead shell temperature reaches the saturation temperature T_H (it is close to the holder temperature T_0) for a short moment of time t_H, which does not exceed 1 second.

Thus, using a cryogenic holder we can protect the target from the thermal radiation of the chamber wall and fix the target temperature in the ranges stated by the technical requirements.

There remains to find out the role of coefficient γ, which describes a degree of the heat contact imperfection. We have stated earlier that its exact value can be determined only

TABLE 3: SHELL TEMPERATURE STABILIZATION (T_I=4.2K) AT DIFFERENT VALUES OF HOLDER TEMPERATURE

T_0,K	8	9	10	11	12
T_H,K	8.016	9.019	10.024	11.025	12.024
t_H , sec	0.212	0.3	0.47	0.62	0.863

TABLE 4. SHELL TEMPERATURE STABILIZATION AT DIFFERENT VALUES OF PARAMETER γ.

γ, %	5	10	30
T_H °K	18.238	18.12	18.04
t_H , сек	19.3	10.02	2.8

experimentally. Therefore, in the current stage of researches we can only vary γ in a wide range of values. Since at γ=50% the value of t_H (which is the time of reaching the saturation temperature) does not exceed 1 second, then in our calculations we take only smaller values of γ : γ = 30, 10, 5 %. The obtained results are shown in Table 4. It is obvious that even in the case of γ = 5% a thermal equilibrium between the shell and the substrate (at minimum value of S_t=20%.) is reached rather quickly – for the time less than 20 sec, and the saturation temperature is close enough to the holder temperature, i.e., $T_H \approx T_0$=18K (see Table 4). In these calculations the initial lead shell temperature is 11K. Thus, our study has shown the following:

1. During target positioning at the center of the experimental chamber the target must be on the cryogenic holder. The holder temperature T_0 is $4.2\ K \leq T_0 < 13\ K$ for hydrogen and $4.2\ K \leq T_0 < 18\ K$ for deuterium. This allows providing the required target temperature during its irradiation in a full compliance with the technical requirements. The initial target temperature T_i must be close to the temperature at which the target was prepared in the fabrication module, i.e., T_i = 10 – 11 K (optimum temperature for the extrusion and *in-situ* methods).
2. The efficiency of heat exchange between the holder and the target depends on (a) relative contact area S_t and (b) coefficient γ. The calculations have shown that (1) the efficient heat exchange between the target surface and the holder is provided even at a very small value γ = 5% and small relative contact area S_t =20%, and (2) the exact value of coefficient γ must be found out experimentally, i.e., it is necessary to make further investigations in this area. Note that the higher the surface treatment and their cleanness, the higher the coefficient γ.

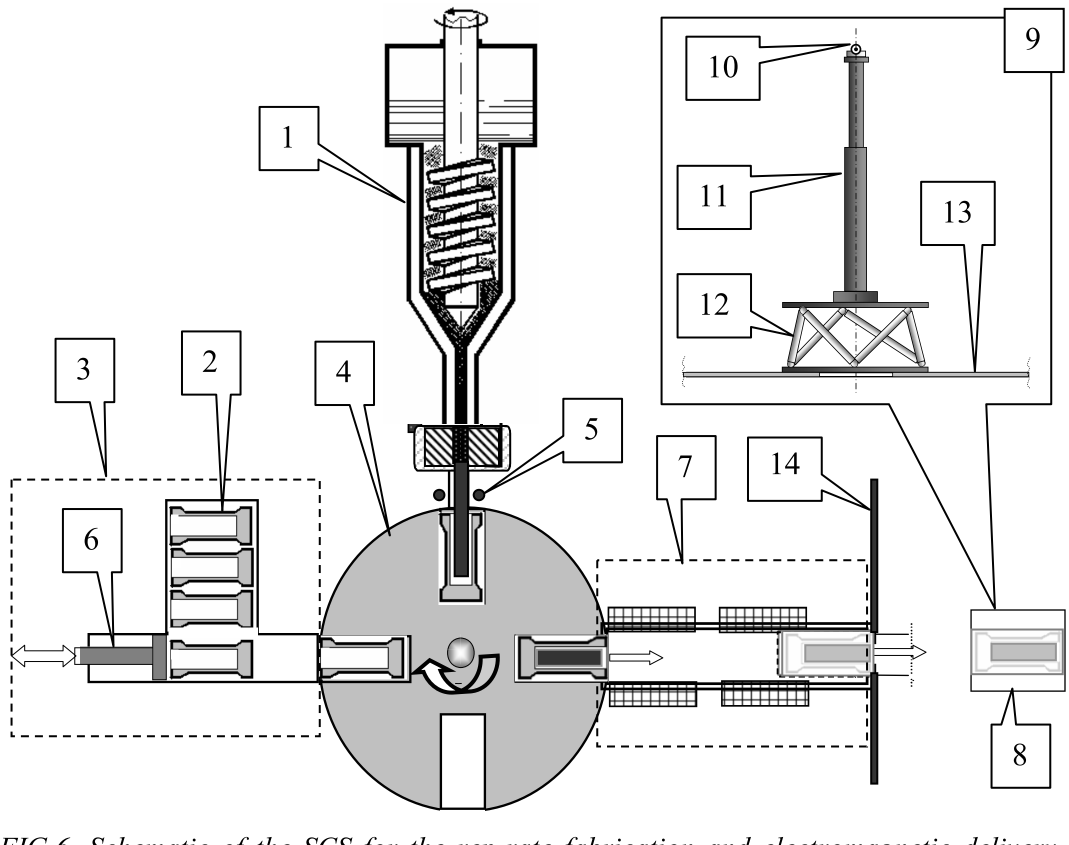

FIG.6. Schematic of the SCS for the rep-rate fabrication and electromagnetic delivery of the free-standing HEDgeHOB targets to the center of experimental chamber. 1- Module for cryogenic core fabrication using extrusion method, 2 – assembly element consisting of Pb shell and a driving capsule; 3 - module for lead shell & driving capsule rep-rate loading into the rotational disk (4); 5 – wire loop; 6 – pusher; 7 – module for finished cryogenic target electromagnetic delivery to the target positioning device (8) disposed in the experimental chamber center; 8, 9 – positioning device top and side views; 10 – target in a holder; 11 – cryocooler; 12 – hexapod; 13, 14 – chamber wall.

4. SCS conceptual design

A peculiarity of the technical approach under the SCS designing is concerned with the requirement of target delivery at the chamber center in a rep-rate mode. To meet this goal the SCS design is based on the FST approach, which makes it possible to deliver the targets into the chamber center with the necessary rate ($\geq$ 1 target per hour). One of the design options is shown in Fig. 6. The distinctive features of this design are as follows: (1) cryogenic core formation using extrusion method, (2) electromagnetic delivery of a target to the chamber centre, (3) the target is inside a driving capsule from magneto-active material at all production steps. The system operates according to the following scenario:

1. Loading the driving capsules with cylindrical lead shells into the rotational disk.
2. Transport (by turning the rotational disk) of one capsule with the shell to the site of assembly with the cryogenic core.
3. Formation of the cryogenic core by means of extrusion, gravitational loading of the cryogenic core into the shell and cutting the upper end of the core using the wire loop. Preliminary characterization of the cryogenic target.
4. Transport of the capsule with the target to the inlet of the delivery system.
5. Electromagnetic delivery of the capsule with the target to the centre of the chamber.
6. Brakeage of the capsule at the outlet from the delivery system and inertial delivery of the target to the cryogenic holder placed in the chamber center.
7. Positioning and final characterization of the cryogenic target.

5. Conclusion

For the first time, it has been analyzed the problem of the rep-rate fueling the LAPLAS experiments with free-standing HEDgeHOB cryogenic targets. SCS conceptual design based on the FST principle is proposed for reliable target fabrication, delivery and positioning at the chamber center. As was found theoretically, target must be placed at the cryogenic holder (at optimal temperature 11 K) in order to guarantee cryogenic core survival during the positioning stage.

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