MECHANICAL MOCKUP OF IFE REACTOR INTENDED FOR THE DEVELOPMENT OF CRYOGENIC TARGETS MASS PRODUCTION AND TARGETS REP-RATE DELIVERY INTO THE REACTION CHAMBER

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Abstract

Targets for high repetition rate facilities are the most challenging issues in inertial fusion energy (IFE) research. At the Lebedev Physical Institute (LPI), efforts are underway on creation of the mechanical mockup of IFE reactor (MM-IFE) for developing the reactor-scale technologies applicable to mass production of IFE targets and their repeatable delivery into the reaction chamber. In this paper, we discuss the current status and further trends of developments in the area of advanced target technologies underlying the R&D program on MM-IFE.

INTRODUCTION

The goal of of IFE research is development of high-precision and mass production technologies for fueling a commercial power plant at the rate of ~10 Hz [1]. The conventional approach to solid layering based on the beta-layering method [2] is unable to ensure the IFE requirements, as it (a) works with targets fixed on a suspension (no repetition rate operation), (b) has a long layering time (more than 24 hours that leads to a large tritium inventory), (c) temperature-dependent behavior of the local defects at the inner surface of a D−T-single-crystal anisotropic layer leads to roughening the layer surface, and provoking to implosion instabilities, (d) has a high production cost (more than $1000/target).

The beta-layering method can form a spherical fuel layer in a uniform thermal environment; however this is inefficient in preventing local defects. Therefore, the modern requirements are asking for development of structure-sensitive methods to develop new layering techniques having a synergistic effect with IFE target needs. This is due to the fact that the progress in plasma implosion up to intensive fusion reactions lies in formation of a given fuel structure that must be isotropic for reaching fusion conditions.

At the LPI, the conception of a mechanical mockup of IFE reactor (MM-IFE) has been proposed to develop reactor-scale technologies applicable to mass production of IFE targets at significant rates (Fig. 1). The LPI program also includes much development work on creation of different designs of the hybrid accelerators for IFE target transport with levitation (or noncontact acceleration systems).

The MM-IFE is a modular facility representing in essence a free-standing target (FST) transmission line (integral part of any fusion reactor) designed to IFE targets production, their noncontact delivery at the laser focus and synchronous irradiation by a laser (1−10 Hz). The MM-IFE consists of 3 main blocks: (1) cryogenic target factory (CTF) operating with isotropic fuel layers of 200−300 μm-thick (Fig. 1a) [1]; (2) cryogenic IFE-target injector operating at overloads < 500g and injection velocities $V_{inj} \geq 200$ m/s [3]; (3) tracking systems for on-line control of the injected targets [4].

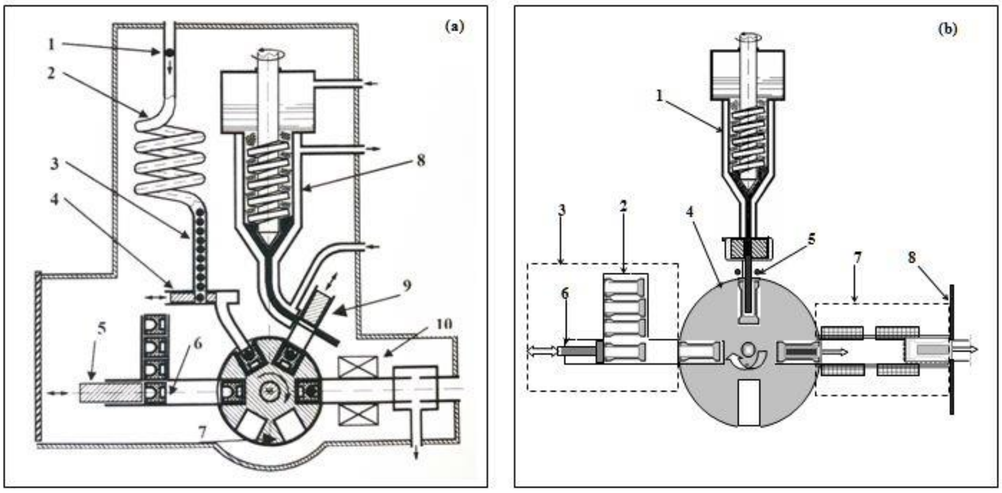

FIG. 1. Repeatable and mass production of the fuel targets/pellets for IFE (a) and for MFE (b) reactors. In (a): 1 – fuel-filled polymer shell, 2 – FST-layering module, 3 – cryogenic targets batch, 4 – shuttle, 5 – pusher, 6 – sabot, 7 – drum of a revolver type, 8 – extruder for protective covers production, 9 – coin for the protective cover formation and delivery, 10 – field coil for "Sabot +Target + Protective Cover" pull out and delivery to the start point of injector. In (b): 1 – extruder of solid fuel pellets, 2 – pellet carrier (sabot), made from superconductor or ferromagnetic, 3 – module for sabot repeatable delivery to the rotating drum, 4 – rotating drum for rep-rate assembly of the units "Sabot + Pellet", 5 – heater for pellets production, 6 – pusher, 7 – linear electromagnetic accelerator (injector), 8 – sabot brake.

Replacement of the FST-layering module, being the main part of CTF, on the solid fuel pellets extruder allows developing the technologies for continuous fuel supply into magnetic fusion energy (MFE) facilities (Fig. 1b).

Basic elements of the MM-IFE have been tested at LPI as prototypes for risk minimization at the stages of MM-IFE construction and start-up. We especially highlight that moving targets are the necessary condition for realizing the repeatable target production at required rates, their mass manufacturing and noncontact delivery.

In this paper, we discuss some challenging scientific and technological issues associated with IFE targets, the current status of the R&D program on MM-IFE and further trends of developments in the area of advanced IFE technologies for high repetition rate laser facilities.

1. TARGET MASS PRODUCTION

The fuel structure is very important for the progress towards ignition. The FST technologies have been developed at LPI [1, 5−9] (Fig. 1 and 2) for a rapid fuel layering via heat conductivity under free-standing targets moving in a single spiral layering channel. A batch mode is applied, and high cooling rates are maintained ($q = 1{-}50$ K/s) to form isotropic ultrafine solid layers. An ultrafine fuel structure (submicron crystalline state called "fine-grained" crystalline or nano crystalline state) supports the fuel layer survivability during target delivery. The total layering time is typically less than 15 s (for targets less than 2 mm in size), which is promising for tritium inventory minimization.

Figure 2 shows the operational scenario of the FST layering module (FST-LM):
— FST-LM works with a target batch at one time at cooling rates $q = 1{-}50$ K/s;
— Targets remain un-mounted (or free-standing) in each production step;
— Transport process is the target injection between the basic units:
Shell Container (SC) — Layering Channel (LC) — Test Chamber (or Target Collector (TC));
— Targets move top-down in a single- or double-spiral LC in rapid succession of one after another;
— All these allow to realize a high injection rate during finished target delivery to the TC (Figure 3);
— High cooling rates combined with high-melting additives to fuel content (Figure 3a) results in creation of a stable ultimate-disordered structure with a high defect density or isotropic medium. For D−T mixture (having the molecular composition: 25% of D_2, 50% of deuterium tritide molecules, and 25% of T_2), just T_2 is considered as a high-melting additive with respect to D_2 and deuterium tritide. An important parameter is the

target lifetime within a temperature interval ΔTex, in which a stable ultrafine fuel structure can exist. Our FST experiments showed that in the case of fuel doping in the range of η = 0.5% − 20% (neon, argon, tritium) this interval ΔTex= ΔTFST had the largest possible range, from 4.2 K right up to the temperature of solid fuel melting at the triple point.

— Isotropic ultrafine layers have an adequate thermal and mechanical stability for the fuel layer survivability under target injection and transport through the reaction chamber [1, 6−8].

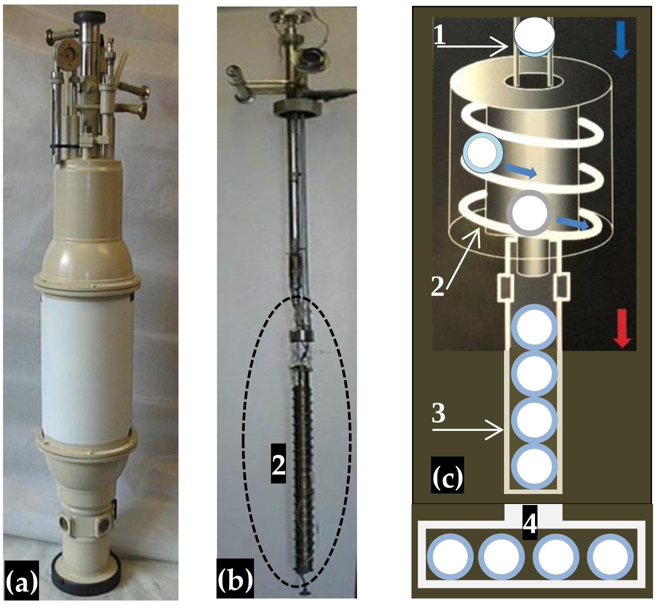

FIG. 2. FST-LM: (a) overview, (b) single spiral LC in assembly, (c) schematic of the repeatable operation of the FST-LM: 1 – gravitation loading of the target with liquid fuel from the SC to the LC, 2 – LC, 3 - vertical target collector, 4 − horizontal target collector.

Demonstration of the targets gravitational loading (one-by-one target injection) from the LM to the TCs (vertical and horizontal) with a rate of 0.1 Hz at T = 5 K is shown in Fig. 3. In future developments we consider the approach based on the FST layering method as a credible path for creating a repeatable operating FST supply system (FST-SS).

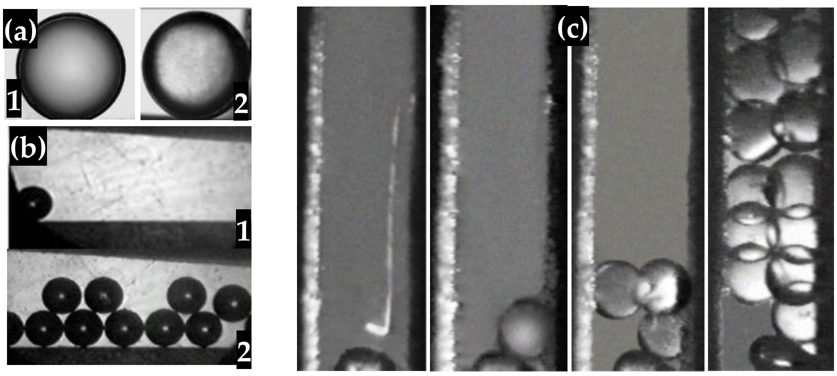

FIG. 3. Results of the FST-LM operation with a rate of 0.1 Hz at 5.0 K. In (a) FST-layering result: 1 − 40-μm-thick D_2 layer with 20% Ne additives in free-standing CH shell of 1.23-mm diameter (20% Ne in order to modeling the D−T fuel), 2 − 44-μm-thick H_2 layer with 5% HD additives in free-standing CH shell of 1.2-mm diameter ; in (b) horizontal TC: 1 − 1 target (0 s), 2 − 10 targets (100 s); in (c) vertical TC: 12 targets (100 s).

The first step in this direction is the development of the next-generation FST-LM for high-gain direct-drive targets, which are the shells of ~ 4 mm in diameter with the shell wall of different designs from compact and porous polymers. The layer thickness is ~ 200 μm for pure solid fuel and ~ 300 μm for in-porous solid fuel. We start with calculation of the FST layering time. In [5] we proposed a model for rapid fuel layering inside moving, free standing targets. It is based on solving the Stephen's problem for moving boundaries between the fuel phases (gas, liquid and solid) and for nonlinear boundary condition onto the outer shell surface (shells ≤ 2 mm). The heat transport outside the target is conduction though a small contact area. At current stage of research the FST model was scalable for IFE targets (~ 4 mm). The modeling results have shown that the FST layering time (t_f) does not exceed 23 s for D2 fuel and 30 s for D−T fuel.

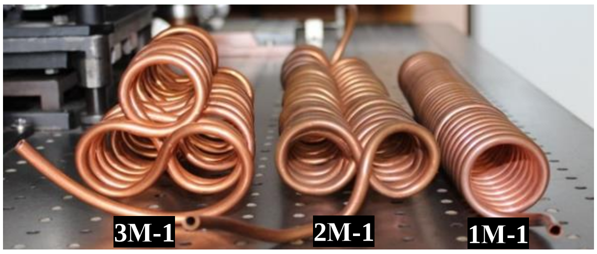

FIG. 4. Different geometry of the LC mockups used in the FST layering module.

The next problem is LC manufacturing for these large cryogenic targets. Model experiments were made with the mockups of different designs, and as a result of which the required LC geometry was found. The time-integral performance criterion is that the target residence time t_r in the LC must be more than the fuel layering time t_f. Fig. 4 show three mockups: mockup 1M-1 (one-fold spiral), t_r = 9.8 ± 0.5 s; mockup 2M-1 (two-fold spiral), t_r = 23.5 ± 1.7 s; mockup 3M-2 (three-fold spiral), t_r = 35.0 ± 2.0 s. These measurements show that 4-mm targets can be manufactured by the FST layering method using n-fold-spiral LCs at n = 2, 3. Note that currently only curved LCs in a specialized geometry (including a conic spiral as well) and moving targets are successful for developing the FST-LM of repeatable operation, which works with a target batch rolling along the LC.

2. TARGET REPEATABLE DELIVERY

During the delivery it is necessary to maintain the fuel layer quality in the process of target acceleration and injection; and for this reason, the target must be placed into a special target carrier (sabot). Using sabots, there occur some contact problems. Because of a tight seal between the sabot and the barrel, any damage to the barrel and the sabot surface will affect the injector performance and sabot reusing.

Recently, we have started the investigation into magnetic levitation as an alternative technology of noncontact manipulation, positioning and delivery of the finished cryogenic targets. In IFE applications, this direction attracts a significant interest due to magnetic levitation (maglev) potential for almost frictionless motion. The transport process with levitation results from the direct use of the diamagnetic characteristics of the HTSC materials. Their unique features can be exploited in the process of levitation and guidance of a HTSC-Sabot as well. The challenging scientific and technological issues associated with this task are being addressed through a combination of materials selections and materials property measurements, mathematical and experimental modeling, demonstration of the HTSC-Sabot acceleration on laboratory-scale tests.

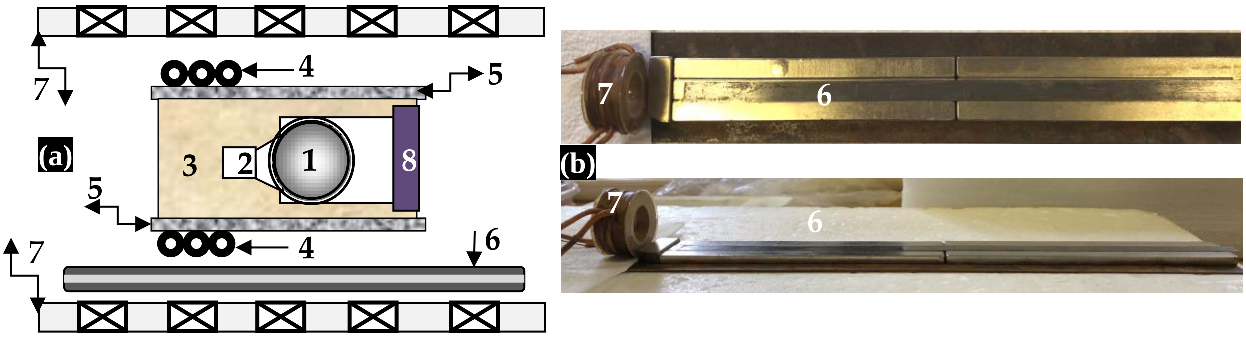

FIG. 5. Schematic of «EM-AC + PMG» accelerator. In (a): 1 − target, 2 − conical support for the target nest, 3 − sabot matrix (polymer), 4 − HTSC-coils (driving body based on superconducting MgB_2-cables), 5 − HTSC-plates for providing a stable levitation along the magnetic track, 6 − magnetic track, 7 − field coils, 8 − protective cover; in (b): experimental setup (top and side view).

The noncontact acceleration system designed at LPI is a combination of the acceleration system (field coils generating the traveling magnetic waves) and the levitation system (permanent magnet guideway or PMG including a magnetic rail or magnetic track) as well as the sabot made from high temperature superconducting (HTSC) elements. Fig. 5 illustrates the operational principle of the noncontact acceleration system. Currently, a concept of hybrid accelerator «EM-AC + PMG» is complete [3] and proof-of-principle experiments confirmed the benefits of our approach.

Fig. 6 shows a set of freeze-frame shots of the acceleration process of the HTSC-Sabot levitating at T = 80 K over the PMG-system. The sabot motion has been driven by the electro-magnetic pulse generated by the field coil. The sabot material is the second generation superconducting tapes based on GdBa2Cu3O7-x (SuperOx, Ltd). The obtained results have shown that the HTSC can be successfully used to maintain a friction-free motion of the HTSC-Sabots, and also to provide a required stability of the levitation height over the whole acceleration length due to the pinning effect. Additionally, using the driving body from MgB_2 superconducting coils as a sabot component (critical current 5000 A at magnetic induction 0.25 T) allows reaching the injection velocities 200 m/s under 400g acceleration at 5-m length [3].

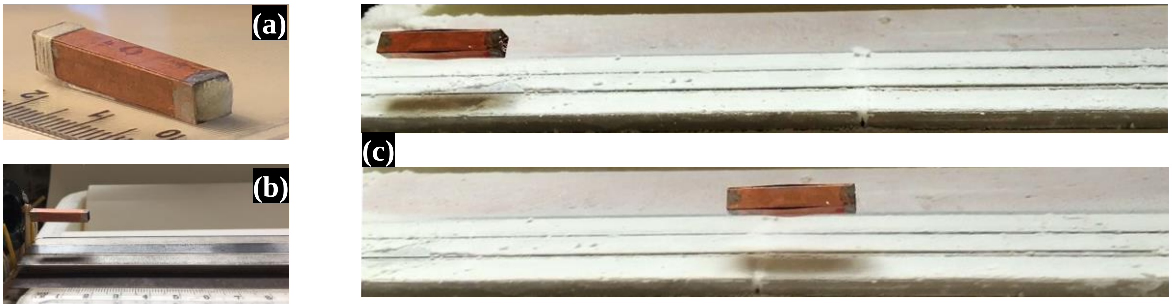

FIG. 6. HTSC-sabot friction-free acceleration by the driving electromagnetic pulse generated by the field coil: (a) HTSC-sabot overview; (b) HTSC-sabot before acceleration; (c) in-time development of the acceleration process.

Note several important aspects related to a practical engineering:
— In our study we have proposed the PMG configuration which allows in-space equilibrium position of the HTSC-Sabot during its acceleration: it goes along a whole magnetic track with the same levitation height and orientation.
— Taking into account that experimentally the HTSC-Sabots keep their speed after acceleration pulse, they can be extra accelerated by using a multiple-stages accelerator.
— Superconducting cables can be used not only in the driving body but also in the field coils. If the coils carry a current, I, less than a critical current, I_C, since large magnetic fields can be generated without heat generation.
— In our model the MgB_2-driving body represents a magnetic dipole (MD). The MD acceleration is carried out by a traveling magnetic wave or ARP at the consecutive switch of the field coils. From the view point of a relative positioning of the ARP & MD, the steady case is realized when the ARP pushes the MD but does not pull it for itself, i.e., the area of a phase (longitudinal) stability is on a forward slope of the ARP. In the accelerating equipment it is referred to as a principle of automatic phasing. This principle will be inherent for the MgB_2-driving body because, as a superconductor, it will be pushed out from the area of a stronger magnetic field.
— Especially note that the injection velocities $V_{inj} \geq 200$ m/s is not a problem for the proposed noncontact schedule of the target delivery. It can successfully be used in creation of a hybrid accelerator for future IFE power plants.

3. TARGET PROTECTION SYSTEM

Target delivery into IFE power plant requires target acceleration (mechanical and thermal loads) and repeatable injection into the reaction chamber (thermal loads). For this reason, the problem of using the cryogenic targets in the IFE experiments or in a future reactor includes not only an issue of fabricating a qualitative cryogenic fuel layer (non-uniformity < 1%, roughness < 1 micron), but also an issue of target delivery at the laser focus under conditions of the layer parameters survival. In our study a number of protection techniques have been examined with the aim of risk minimization in the process of target acceleration and injection.

A promising direction for survivability of fuel layers is application of external target protective coatings to reduce the risks of the fuel damage under the radiation exposure from the hot walls of the reaction chamber: cryogenic coatings (from the solid D_2, H_2, or Xe), metal coatings from Au, Pt, Pd and their alloys, application of a double protection: "Metal+ Cryogenic" (Fig. 7a). Below we demonstrate the practical possibilities of this direction.

To obtain the results in Fig. 7b, an additional operation has been added in the FST formation cycle. First, the metal coating made from Pt/Pd is deposited on the CH-shell. Then the shell is filled with the D_2 gaseous fuel having the doping agents (3%Ne additives). The next step is D_2 layer formation by the FST layering method.

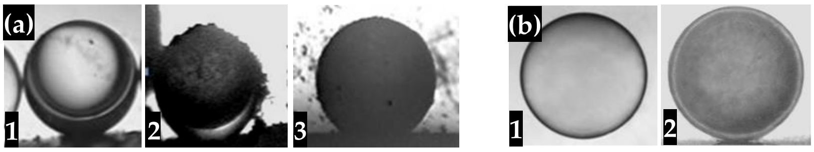

FIG. 7. Different protective coatings. In (a): double protection "Pd-coating (150 Å) and Cryogenic O_2-coating": 1 − 1.2-mm CH-shell at 14.6 K before the experiment (liquid H_2 inside), 2 − in the top part of the shell (from the outside) there is a solid deposit of oxygen (T_{tp} = 54.3 K), 3 − after operation of the piezoelectric vibrator, the oxygen snow becomes redistributed onto the outer shell surface; in (b): single protection "Pt/Pd-coating (200 Å)": 1 − 1.5-mm CH-shell before the experiment, 2 − cryogenic target at 5.0 K with a uniform D_2 layer of 50 μm produced by FST.

The sabot is also a special element of the target protection system [8]. An important feature of its design is the shape of a target nest. Our study has shown that a proper choice of the nest shape makes it possible to significantly increase the upper limit of the permissible overloads and to minimize the injector overall dimensions. Based on the discrete-continuous physical model of shell stress, a simulation code SPHERA was developed that allowed to define the stress and deformation arising in the target during the acceleration process. A shape analysis of the sabot bottom (in the target nest area) in terms of the target overload during its acceleration has been performed for three sufficiently different cases: (1) flat bottom, (2) semi-spherical bottom with $R_n > R_t$ (R_n and R_t are the nest and the target radius, respectively), (3) conical bottom (Fig. 5). Some important conclusions followed from the calculations are enumerated below:

— Permissible target overloads for a flat bottom is 50 times smaller than for semispherical supports with clearance less than 5 μm; at clearance more than 20 μm stresses arising in the target are close to those of the flat bottom;

— Application of a conical bottom with an angle in the cone basis equal to 87^0 provides a 20-times increase in the permissible target overloads; technologically, the conical bottom has much more promise than the semi-spherical one.

Next step is a shields (or cover) for application to protect injected target from a head wind of a residual gas. In [10] we have proposed a new design of a protective cover made from solid xenon or deuterium. In our current study we have analyzed the cover and the target interaction with the reactor chamber environment using the Direct Simulation Monte Carlo (DSMC) approach as well as using results of numerical studies of gas flows interaction with bodies. The following relations were considered:

— Equation of motion

$$L = Ut - F_D t^2 / 2M_b \quad (1)$$

— Velocity in a laminar circular wake behind the cover:

$$u(x,y) = U[(\pi C_D)/32] \cdot [(2R/x) R F_D] \exp(-\eta^2) \quad (2)$$

— Drag force equation for a sphere:

$$\mathrm{F}_D = -(3/4) a^2 n u (m_g k_B T / 2\pi)^{1/2} F_1 \mathrm{k} \quad (3)$$

where $F_1 = F_{1o} + F_{1p}$, $F_{1o} = 8\pi(8+\pi)/9$, $F_{1p} = -21.28/\xi^2$ (for 2 equal spheres), **k** is the unit vector in a target direction movement, L is the distance between the body (target or cover) and the burn area, R is the characteristic dimension (target or cover), t is in-flight time, $\mathbf{F_D}$ is the drag force, M_b is the mass (target or cover), U is the injection velocity, u(x,y) − current velocity, η and ν are the dynamic and kinematic viscosity of a residual gas, M is the Mach number, m_g is the mass of residual gas, a is the sound speed in gas, k_B is the Boltzmann constant, F_{1o} and F_{1p} are the dimensionless drag coefficients, ξ is the dimensionless distance measured in target radii, C_D is the coefficient of gas molecules accommodation by the target surface. The following parameters were used in estimations: injection speed is 250 m/s, residual gas is Xe at 0.5 Torr, reactor chamber radius is 5 m, a cylindrical cover from solid Xe with a mass of 87 mg, the target mass is 5 mg.

In the drag force estimations two cases were considered: solitary and joint flight of target and cover. Correction for the solitary case (effect of wake) is about 30%. The estimations showed that, due to the drag force action, the distance between the target and the cover rises from the initial 1 mm at the moment of injection up to 15 mm at the center of reaction chamber. Thus, the drag force provides necessary separation of the cover and target inside the reaction chamber. Protective cover forms a wake region (Fig. 8a) with reduced flow velocity and temperature and effectively reduces the gas heat flow by a factor of 4-to-5, which is in a good agreement with calculations reported in [11]. Thus, the concept of protecting the direct drive target in the reactor chamber by a cover moving ahead can be considered as a possible way of solving the target delivery problem. Note, that the problem of target survival is the more difficult the higher the target temperature at the moment of injection. Estimations showed that radiation heat flow from the chamber wall is an order of magnitude higher than the gas heat transfer (Fig. 8b). Therefore, target injection at 5 K is more preferable than at 17 K.

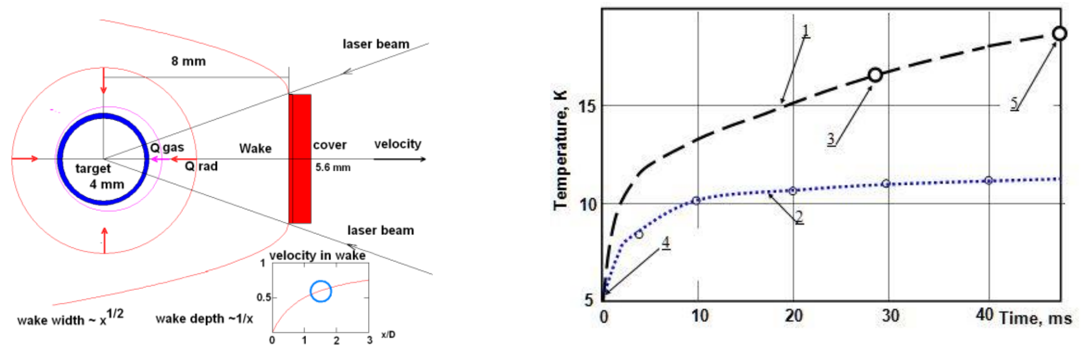

FIG. 8. Protective cover: (a) protective cover forms a wake area in the fill gas to protect a target from the head wind and to avoid the convective heating; (b) target thermal history in IFE chamber under exposure of the wall radiation and gas convection: 4-mm targets with D_2 fuel (200 µm), reactor wall temperature − 1773 K, residual gas Xe − 0.5 Torr (1 – target without reflecting layer, 2 – target with reflecting layer, 3 – injection at 17 K, 4 – injection at 5 K, 5 − 18.5K, point of destination).

Basing on these results as well as on the results presented in Sections 2 and 3, we propose a multiple target protection system for the effective delivery of a cryogenic target without its damage:
1. Cryogenic layers formation with an isotropic ultra-fine fuel structure (which can be referred to as layers with inherent survival features) to reduce the target sensitivity to the external thermal and mechanical loads.
2. Use of friction-free acceleration of the "HTSC-Sabot + Target" assembly to reduce the heat flux on the target under development of a noncontact delivery system with linear or circular accelerators.
3. Use of conical supports for a target nest in the sabot to reduce the mechanical loads during acceleration of the "HTSC-Sabot + Target" assembly.
4. Use of outer coatings (cryogenic, metal) in the target design to reduce risks of cryogenic layer damage as a result of target heating by thermal radiation of the hot chamber walls.
5. Co-injection of a target and a protective cover from freezing gases (D_2, Xe) to reduce risks of cryogenic layer damage as a result of target heating by hot residual gases in the reaction chamber.
The important remaining factors of the research include issues of complex technology optimization and system integration.

CONCLUSION

The purpose of this work is to study a repeatable target production and methods of their noncontact delivery in the scope of MM-IFE program. Various arising problems were considered, and methods of their decision are developed and experimentally tested. In the course of the researches, thermal, mechanical and levitation modeling (theoretical and experimental) are important factors in planning experiments on MM-IFE and studding IFE targets.

Of particular interest in IFE research from scientific and technological viewpoints is a cryogenic target that must be delivered to the target chamber center at a rate of about several Hz and more. Therefore, the IFE target fabrication is focusing on methods that will scale to a high rep-rate and cost-effective target production.

The top-level requirements to successful target fabrication and injection are target material selection and fuel layer structurization. The following aspects are of key importance:
1) Target mass-production:

● Target materials must satisfy a wide range of required and desirable characteristics: optimal micro-structural design and materials selection allow one to obtain chemical, physical and mechanical characteristics for specific applications;
● Target fabrication capabilities and technologies must take into account the structure particularities of the solid fusion fuel;
● Fusion fuel must have an adequate thermal and mechanical stability for their quality survival in the processes of target acceleration and injection during its delivery.
2) Cost-effective target production:
● Minimization of time and space for all production steps;
● Moving targets co-operate all production steps in the FST transmission line that is considered as a potential solution of passing from one-of-a-kind techniques to about 1, 000,000 targets each day
● Moving targets are the necessary condition for realizing a repeatable target production at required rates and their noncontact delivery at the laser focus.
3) Survivability of a fuel core:
● Layers with inherent survival features (fuel layer structurization − the grain size should be scaled back into the nanometer range);
● Noncontact delivery system;
● Multiple target protection methods (outer protective cryogenic layers, metal coatings of different configurations and compositions, nano-coatings for specific applications, co-injection of a special protective shroud ahead of the target, etc).

For the IFE, all techniques must be integrated into an FST transmission line capable of producing about 1 million targets each day. Therefore, future researches on MM-IFE are needed to guide other R&D programs and to predict the behavior of IFE targets during their layering, delivery and transport through the chamber environment. In addition, the MM-IFE allows reducing the cost of developments because it is intended to test the reactor-scaled technologies and to identify key issues for IFE commercialization. Implementation of MM-IFE program will be useful in the technical requirement developments for creation of a laser energy power plant.

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