LEBEDEV PHYSICAL INSTITUTE
RUSSIAN ACADEMY OF SCIENCES

Физический институт имени П.Н.Лебедева
F I A N

Lebedev Physical Institute of RAS (LPI)

Thermonuclear Target Laboratory

STATUS OF THE FST TECHNOLOGIES FOR HIPER TARGETS: RESULTS OF MATHEMATICAL MODELING & MOCK-UPS TESTING

Elena Koresheva and leading specialists of the ISTC Project #3927:

I.V.Aleksandrova, I.E.Osipov, A.I.Nikitenko, T.P.Timasheva, A.N.Aleksandrov, E.L.Koshelev, V.A.Kalabuhov, A.I.Kupriyashin, S.M.Tolokonnikov, L.V.Panina, A.A.Belolipetskiy, E.A.Malinina, I.D.Timofeev, A.I.Safronov, G.S.Usachev

3rd European Target Fabrication Workshop, 29 September- 1 October, 2010, Oxford, UK

OUTLINE

- **Background for the FST technologies developed at the LPI (FST = free-standing target)**

- **FST approach to fabricating the targets of a HiPER-class (shock ignition design): results of the feasibility study & preliminary design of the FST-layering module**

1. Fuel filling of a batch of free-standing shells
2. Depressurization of the shell container with a batch of fuel filled shells
3. Fuel layering inside moving free-standing shells (FST method)
4. Approaches to characterization of a HiPER-scaled cryogenic target
5. Draft design of the FST - layering module for HiPER-scaled targets
6. FST - layering module / injector connection

- **Summary**

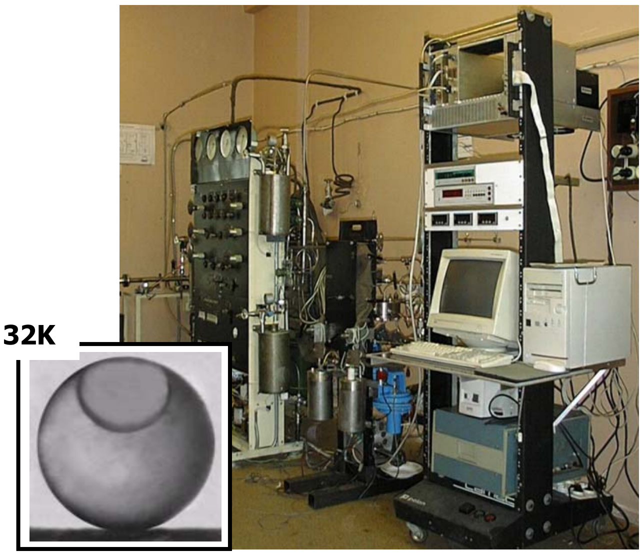
BACKGROUND FOR THE FST TECHNOLOGIES*
(FST = FREE-STANDING TARGET)

---

*/This work has been implemented in the frame of 5 projects:

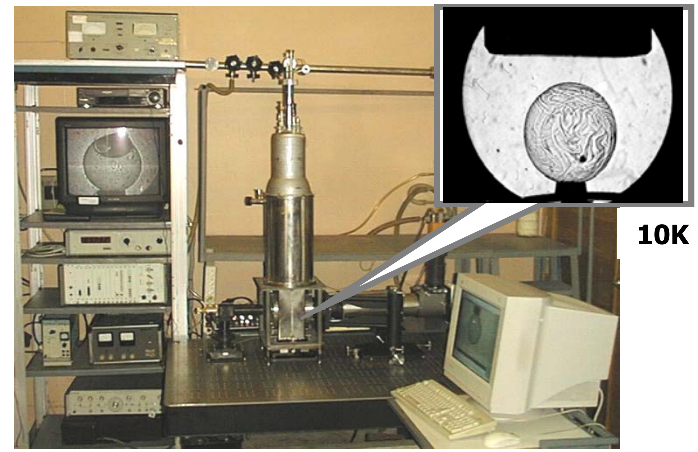
- ISTC Projects #512 & #1557
- IAEA Contracts # 11536 & 13871
- RFBR Project # 06-08-01575-a

The FST system created in LPI operates with free-standing targets at each production step. Its operability has been demonstrated for CH shells of 0.8÷1.8 mm-diam & cryogenic layers of 10-to-100 μm-thick. Layering time is 4-to-15 sec. Production rate is about 0.1 Hz

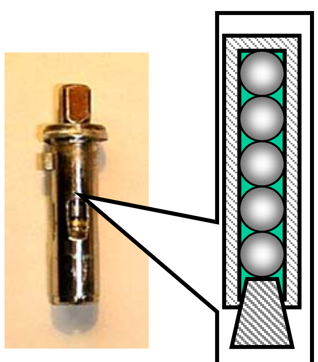


Computer-aided fill facility
for spherical shells diffusion filling with gas up to 1000 atm at 300 K

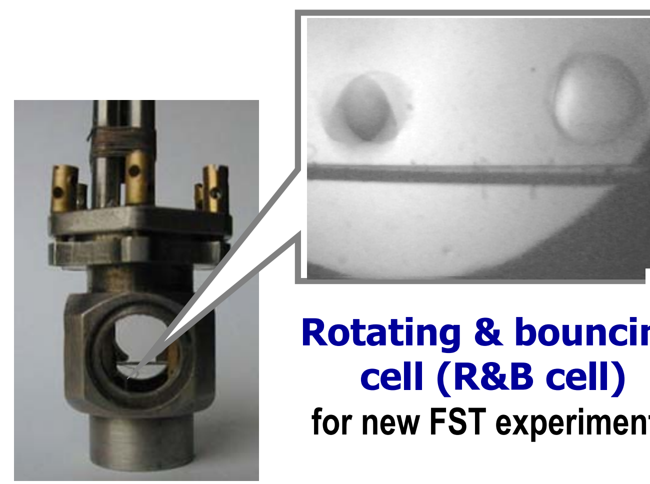
FST layering module
for fuel layer formation inside moving free-standing shells



A 100-projections visual-light tomograph
for precise control of the free-standing targets quality



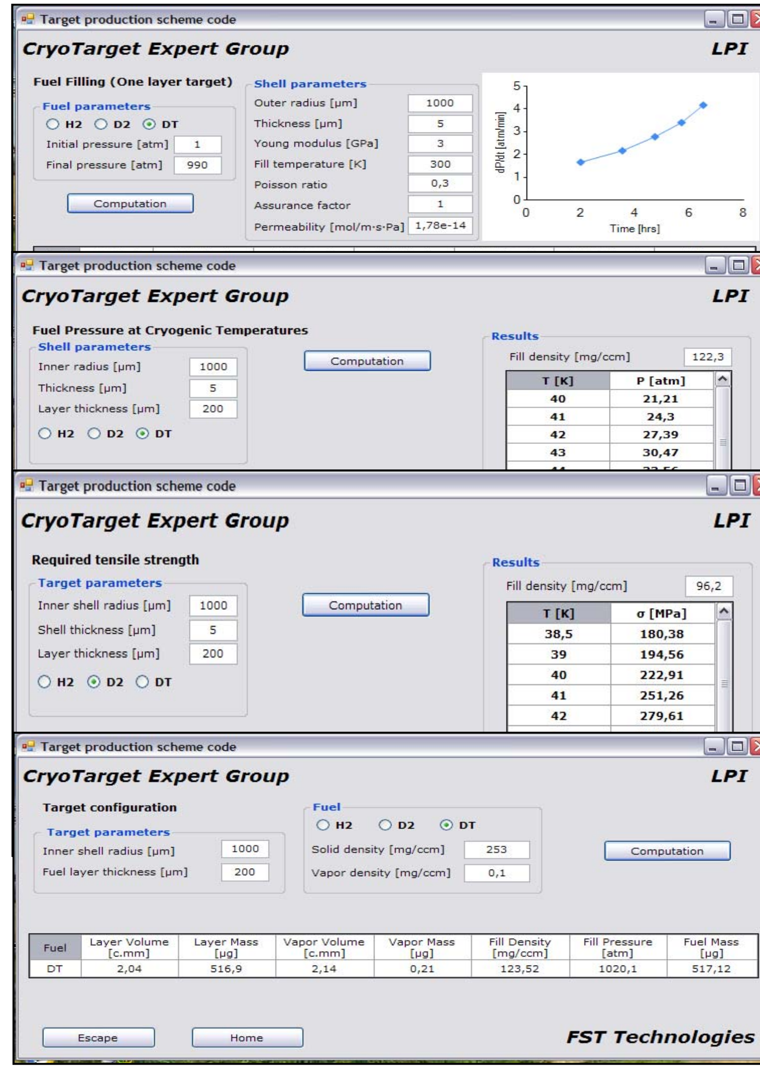
Shell container
for transporting a batch of fuel filled shells at 300 K



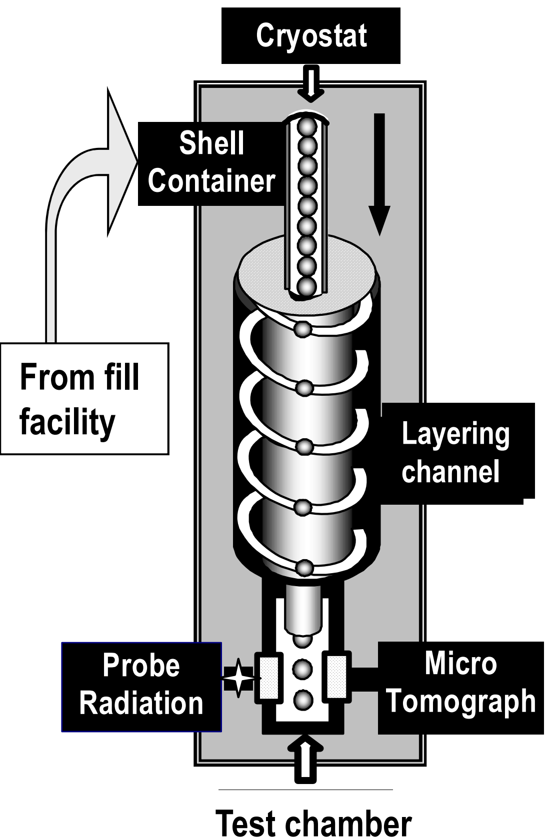
Rotating & bouncing cell (R&B cell)
for new FST experiments

Special software developed at LPI has been used for the FST experiment optimization that ensures risk minimization of shell destruction at each production stage

- **Target parameters:** number of layers, layer material, layer mass, thickness & diameter
- **Fuel filling** a batch of free-standing shells with fuel (ramp filling regime ΔP=const): P_{fill} , ρ, P/dt, t
- **Depressurization** of the shell container: T_d = temperature, when the shells do not crack by the inner pressure (for different σ & P_{fill})
- **Fuel layering**: t_f = layering time, T_{in} = temperature of the shell input into the layering channel
- **Layering channel geometry**

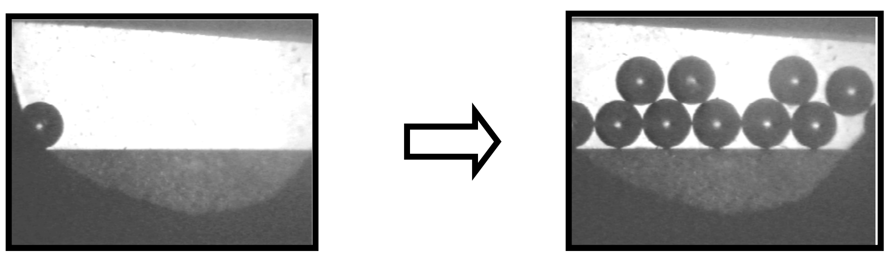


Main principles of the FST layering module operation



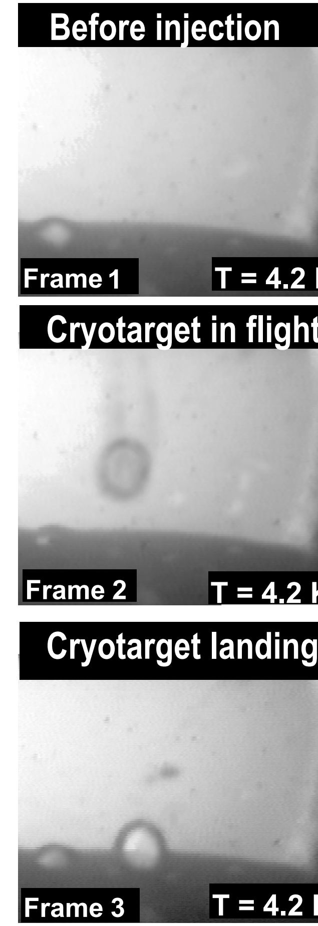
Schematic of the FST layering module

1. Free-standing spherical targets must move in the layering channel (LC)
2. Uniform layer formation goes due to random target rotation during its rolling in the spiral LC
3. Fuel freezing is based on target conduction cooling through the target/LC wall contact area
4. Transport process is target injection between shell container → layering channel → test chamber



t = 0 **100 sec**

Repeated target injection to the test chamber at 4.2 K: f = 0.1 Hz



Injection process inside the test chamber

Fine features of the FST system developed at LPI

- **CAPABLE OF HIGH REP-RATE CRYOGENIC TARGET FABRICATION:** 0.1 Hz rep-rate has been demonstrated for 1 mm-diam cryogenic targets
- **CAPABLE OF PRODUSING AN ISOTROPIC ULTRAFINE FUEL LAYER,** which minimizes risk of fuel layer degrading under the heat- and g- loads arising during target delivery
- **MINIMUM TRITIUM INVENTORY**

  (1) minimal dead volume during the fuel filling

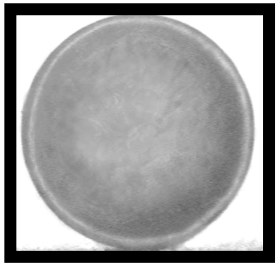
  (2) extremely short layering time: τ_f **< 15 sec**

  */Ref.: traditional methods require τ_f **> 5 hrs**
- **INEXPENSIVE**

  "You can do it only for 360 k$ (the filling system that GA designed and built for Rochester cost ~30 M$ or about 100 times as much!!)"– J.Hoffer (LANL, USA) to E.Koresheva, Sept. 30,1999

METHOD FST + small additives

- CH shell of 1.5 mm-∅; 50 μm-thick ultra-fine layer from 97%D2 + 3%Ne.
- The shell is covered by the outer reflective layer from Pt/Pd (200 Å – thick)

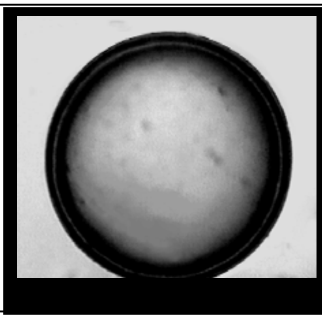


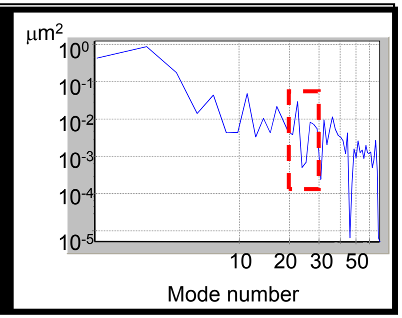
TARGET PRODUCTION SCHEME

1. Depositing the over-coating layer from Pt/Pd onto the polystyrene shell
2. Filling the shell with D2 fuel having 3% additive of Ne
3. Forming a solid layer inside this shell by the FST layering method

METHOD FST + large additives

- Left: CH shell 1230 μm-diam.; 41μm-thick solid layer of 80%D2 + 20%Ne
- Right: Fourier-spectrum of bright band shows that layer roughness rms ≤ 0.15 μm for modes 20-30





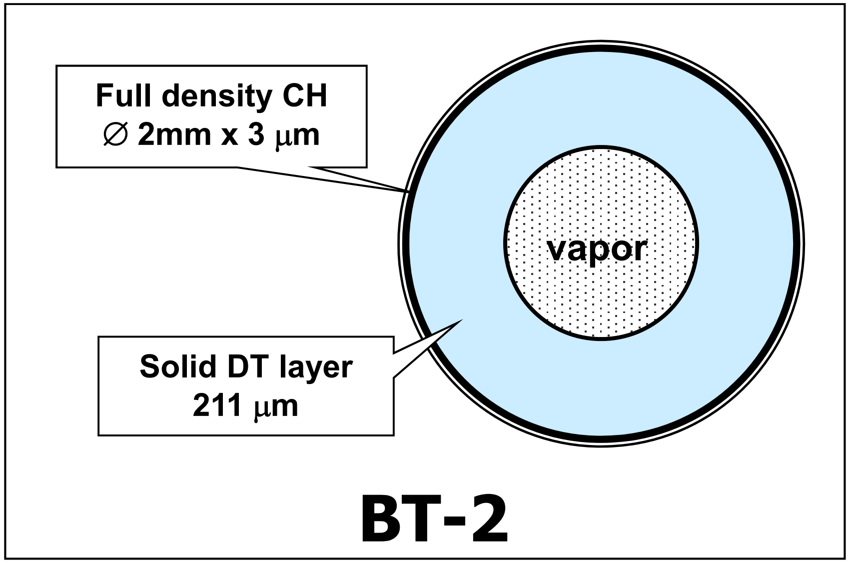
FST APPROACH TO FABRICATING THE HiPER-SCALED TARGETS (SHOCK IGNITION DESIGN): RESULTS OF THE FEASIBILITY STUDY & PRELIMINARY DESIGN OF THE LAYERING MODULE*

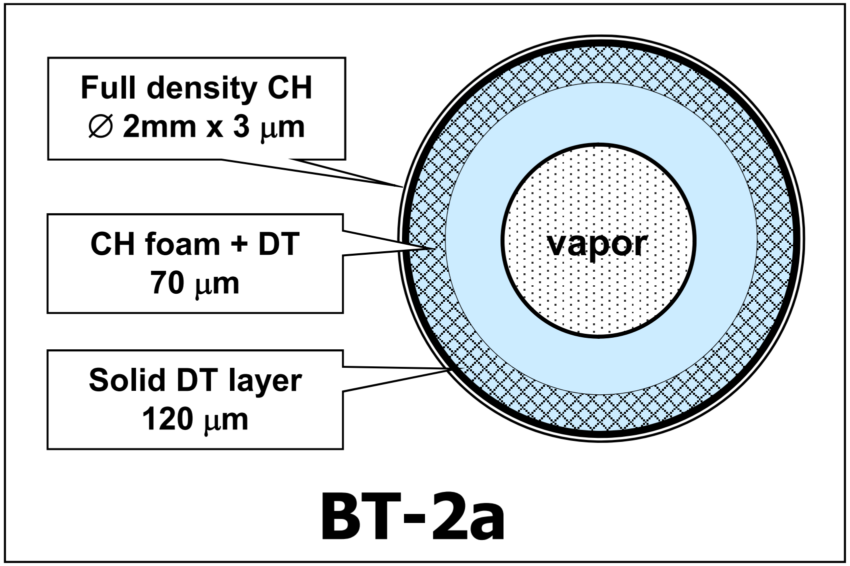
---

*/This work is performed in the frame of the ISTC Project #3927 with the STFC (UK) as a Partner

We consider the baseline target (BT) design proposed for shock ignition experiments on the HiPER facility (~300 kJ)

[S.Atzeni et al., Phys. Plasmas 14, 2007; M.K.Tolley et al., 22 IAEA FEC, 2008]





- **Material under consideration** (recommended by the Partner and other experts)

  Full density polymers (outer shell in BT-2 & BT-2a): **polystyrene, polyimide, GDP**

  Foam polymers (inner foam shell in BT-2a): **HIPE polystyrene, DVB**

  Fuel layer (solid at T < Ttp): **D2 and DT-mixture**

Choosing the database information concerning the properties of the material of the BT-2 & BT-2a layers

- **To carry out the optimization calculations for the FST layering experiment, it is required to have information on the properties of shell-wall material & fuel**

  by 10 characteristics for BT-2

  & by 17 characteristics for BT-2a,

  including the following data at room- and cryo- T :

  - tensile strength, elastic moduli, burst/buckle pressures

  - gas permeability factor

  - thermal conductivity, thermal capacity, thermal expansion coefficient & etc.

Analysis of available scientific sources made it possible to find quite a number of required characteristics. But, the data for the mechanical properties at room- & cryo- T of the foams and full-density polymers (except polystyrene) were not found.

Full density polymers				
Material		Polystyrene	Polyimide	GDP
Density (ρ), kg/m^3		1050	1400	1200-1040
Ultimate tensile strength (σ), MPa	300 K 100-40 K	20-30 44-68	100 - 400 ?	300 ?
Ultimate compressive strength (σ1), MPa (300K)		75	?	?
Young's modulus (E), GPa (300 K)		1.0-4.2	3 - 15	1.4-2.6
Poisson's ratio (ν), (300 K)		0.325-0.33	?	?
Thermal conductivity (λ), Wt/(m ·K)	300 K 40 K	0.154 0.095	0.14-0.20 ?	?
Thermal capacity (c), J/kg·K	300 K 40 K	1260 226	10^{14}-10^{15} ?	?
Permeability factor mol·m/m²·Pa·s (300K)	D_2 DT	3.5-6 10^{-15} 3 10^{-15}	1.8 10^{-14} ?	6.5 10^{-15} ?

Foam polymers			
Material	Highly-porous HIPE polystyrene	Copolymer of 3-5% divinil-benzene with styrene (DVB)	Resorcinol-formaldehyde (RF)
ρ, kg/m^3	15-700	100	100 - 200
σ, MPa	?	55.1-62.0	?
σ1, MPa	0.16-5.2 (calc.)	?	?
E_p, MPa	5.6-21 (calc.)	0.17	?
Pore size, μm	1-10	1-3	0.02- 0.17
Pore type	open	closed & open	open
λ, Wt/(m ·K)	?	?	?
c, J/kg·K	?	?	?

Risk minimization of targets damage under the FST-layering experiment requires to carry out the research on the mechanical properties of HiPER-scaled shells at room and cryogenic temperatures.

Concept of the layering module for HiPER-scaled targets is based on the FST- technologies

❑ **Test models of the general units of the layering module (LM) have been created & tested**

SC ⇨ **S**hell **c**ontainer ⇨ it is the intermediate unit between the fill system and the layering module (LM)

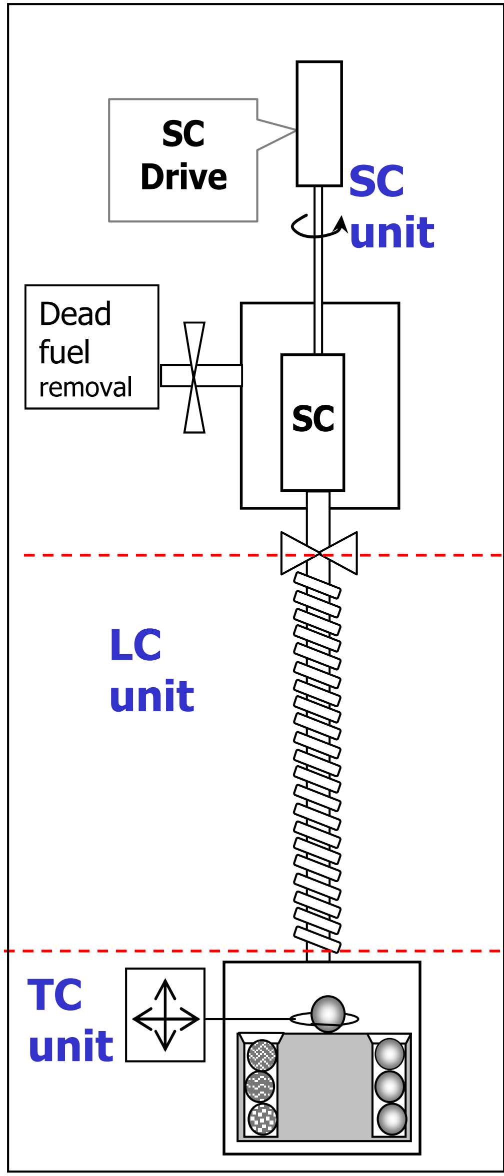
LC ⇨ **L**ayering **c**hannel ⇨ it is the formation unit of a cryogenic layer by the FST layering method

TC ⇨ Optical **t**est **c**hamber ⇨ it is intermediate unit between the LM and the delivery system

❑ **Major stages of the FST production cycle were determined**

1. **Fuel filling** of a shell batch placed inside the SC
2. **SC transport** from the fill system to the LM at 300 K
3. **SC cooling & depressurization** without shells destruction
4. **Shells injection** one by one from the SC to the LC
5. **FST layering** in the free-standing targets moving inside the LC
6. **Cryogenic targets injection** one by one to the TC
7. **Cryogenic target quality control**
8. **Cryogenic target delivery** to corresponding collector

❑ **Special software developed at LPI has been used to optimize the main stages of the FST production cycle**

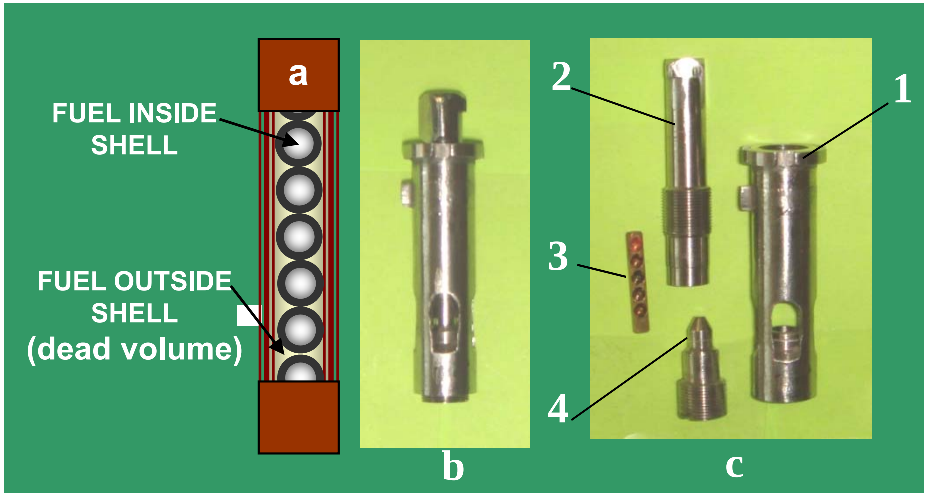


Shell container for manipulation with a batch of HiPER-scaled free-standing shells

1. Shell container (SC) is intended for
- Filling a batch of shells with D2 gas (up to 1000 atm at 300K);
- Shells transport at room temperature;
- SC depressurization at cryogenic temperatures

2. The SC designed for shells of a HiPER-scale (∅ ~ 2 mm) allows to use the existing high-pressure chamber of the fill facility. For this purpose, the new SC must contain 5 shells.

Transport of a batch of fuel filled shells using miniature shell container



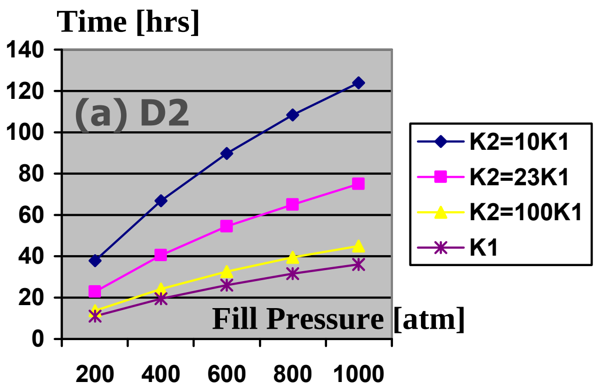
SC test specimen has been developed for HiPER-class targets
(a) schematic, (b) general view, (c) SC integral parts; 1- frame; 2 – insert; 3 – separator; 4 – locking cone

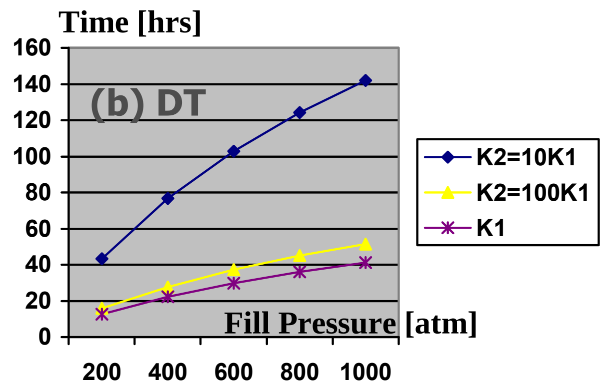
3. The SC prototype was made with the insert–cone contact pair from steel 10X11H23T3MP – invar (36HX) material.

The tightening torque of the insert–cone contact pair was measured to be $M \leq 12$ kg·cm

Expert examination results for the stages of fuel filling and shell container depressurization

Fuel filling: GDP- polymer (or polystyrene) – optimization for the ramp-filling operational regime of the compressor





► **BT-2**: one-layered shell
Pf = 985.82 atm (D2),
Pf = 1046.63 atm (DT)

► **BT-2a**: double-layered shell
Pf = 878.3 atm (D2),
Pf = 918.8 atm (DT)

The fill system existed at LPI can be used for HiPER-scaled targets filling with D2-fuel

Shell container depressurization

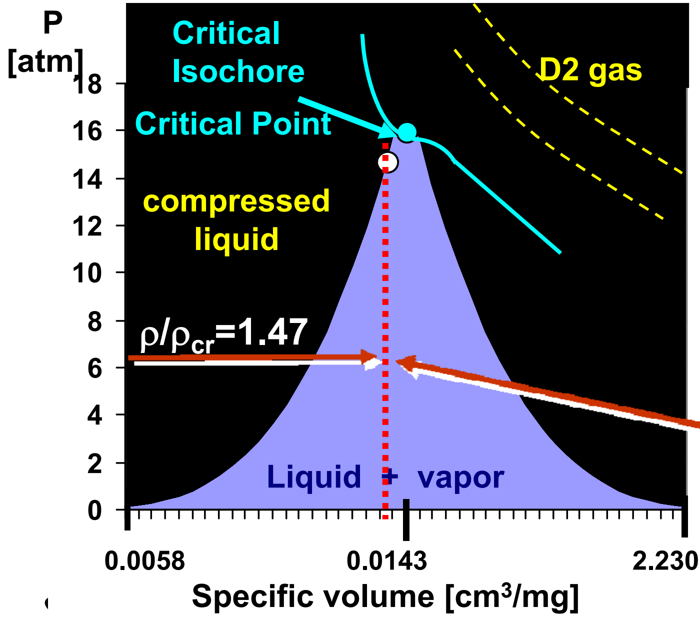
Target	Tensile Strength	Conditions	Tensile Strength	Conditions
BT-2	**σ≥ 450 MPa**	**Gas fuel removal; T>Tcp** (39.4 for DT)	**σ < 350 MPa**	**Liquid fuel removal;** **POLYSTYRENE: 20 K< T $\leq$ 31 K**
BT-2a	**σ≥ 350 MPa**	**Gas fuel removal; T>Tcp** (39.4 for DT)		

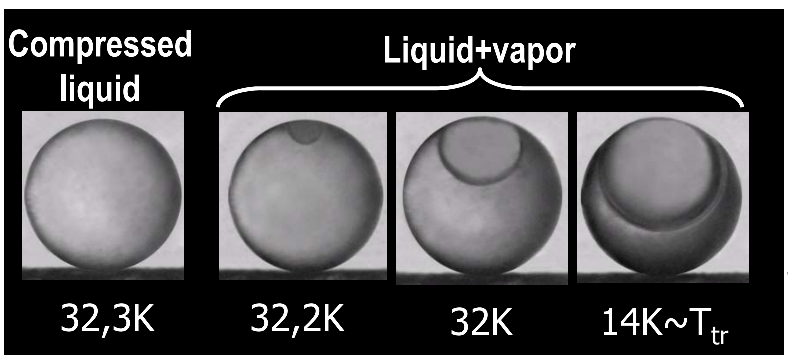
- SC depressurization when the fuel is gaseous (T > Tcr) is possible only for high-strength shells: σ ≥ 450 MPa (BT-2) and σ ≥ 350 MPa (BT-2a)

- At lower strength (example: polystyrene σ=30-to-100 MPa), the depressurization is possible only if the fuel is in a compressed liquid or "liquid+vapor" state

Expert examination results for the FST–layering stage: BT-2 design with polystyrene shell and D2-fuel layer

PV diagram: D2-fuel inside a closed shell





Target cooling

Computation results for BT-2

(CH shell: ~2 mm-diam, 3 μm-thick; D2-layer: 211 μm -thick)

FST method	Contact Area R	τ_{liquid}	τ_{solid}	Layering Time
Cooling from T_{in} to T_{tp}	88.6 μm	**5.9 sec**		**9.7 sec**
Transition at T_{tp}	82.7 μm		**3.8 sec**	

Optimization parameters of the FST experiment (D_2-fuel)

- Required fill pressure: **985.82 atm**
- Formation isochore: **ρ=97 mg/cm³** **ρ/ρ_{cr}=1.47**
- Bubble point: **37.4 K**
- Depressurization temperature Td: **31.0 K**
- Initial fuel state (before layering): **"liquid+vapor" at 31 K**

Configuration of gas-liquid boundary at different temperatures for the case of $\rho/\rho_{cr} > 1$

experiments made for H2: ρ/ρ_{cr} = 1.33, Pf= 765 atm

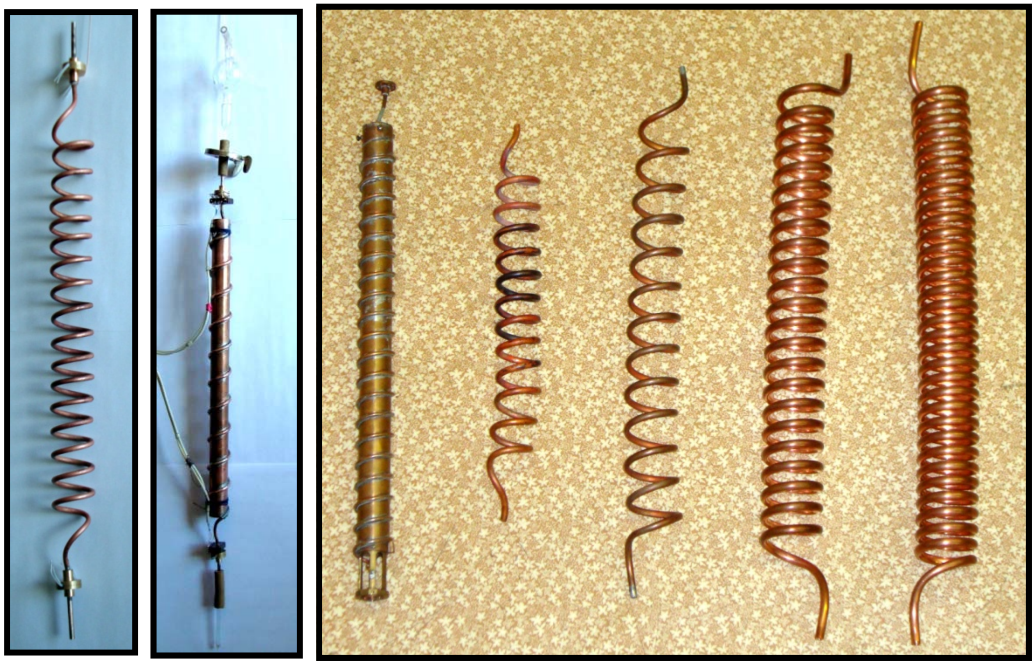
ρ/ρ_{cr} = 1.61, Pf=1100 atm

Experimental campaign to examine the motion of HiPER-scaled targets in the FST layering channel: surrogate targets & LC mock ups

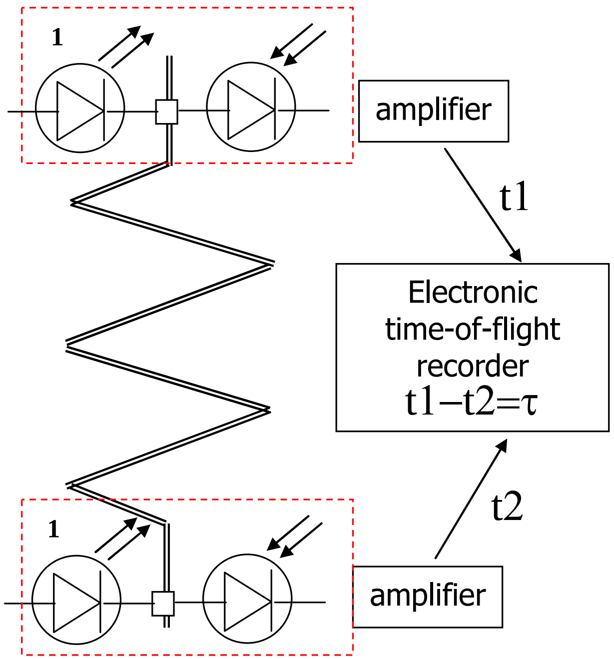
For tests, we selected polystyrene shells with a weight and ∅ close to those of BT-2 (0.59 mg, 2094 μm)

№ of shell	1	2	3	4	5	6	7	8	9	10
Weight, μg	364.8	504.5	630.2	782.0	594.4	598.0	591.0	504.0	741.0	579.0
Outer ∅, μm	1952	1988	2096	2260	2082	2088	2029	1988	2200	2079
ΔR, μm	30	40	45	48	43	43	45	40	48	42

*/ density of polymer shell's material, $\rho = 1.05\ g/cm^3$



A set of the layering channel (LC) mock ups with different parameters: number of turns (ω), inclination angle (α), spiral height (H) & total length (L)

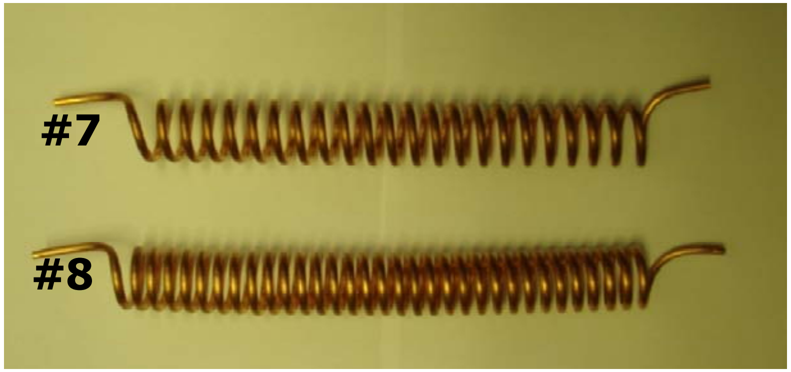


Schematic of measuring the time of target movement inside the spiral LC: 1 – optronic pair made from the "АЛ107Б" IR-diodes

The motion of HiPER-scaled targets inside the FST layering channel must meet the requirement:

$\tau_{res} \geq \tau_{form}$ = 9,7 sec

Test object: 2 mm-diam CH shell with a weight equal to those of BT-2 (0.59 mg)



General view of the test models #7 & #8, which allow to meet the requirement on τ_{res}

Parameters of the #7 (#8)

- Spiral OD 46 mm
- Cu tube OD 6 mm
- ω = 23 (33)
- $\alpha \sim 7^0$ (5^0)
- H= 350 mm (360 mm)
- L= 3 m (4.27 m)

Mock-ups test results

3 mTorr inside the channel, T=300K

№	#7 ($\alpha \sim 7^0$)	#8 ($\alpha \sim 5^0$)
	τ_{res} [s]	τ_{res} [s]
1	10.8	20.1
2	9.3	17.7
3	9.7	16.3
4	10.0	17.5
5	9.1	16.0
6	10.0	16.3
7	-	15.1
8	-	14.9
9	-	15.1
10	-	14.9
Average	**9.8** ±0.46	**16.4** ±1.18

The obtained experimental results are taken into account under the development of the FST layering module for the HiPER-scaled targets

Target parameters control (1): Micro-tomograph-aided characterization of HiPER-scaled targets

[E.R.Koresheva et al. JRLR 28 N2 2007]

Science & technology base created at LPI for precise target characterization

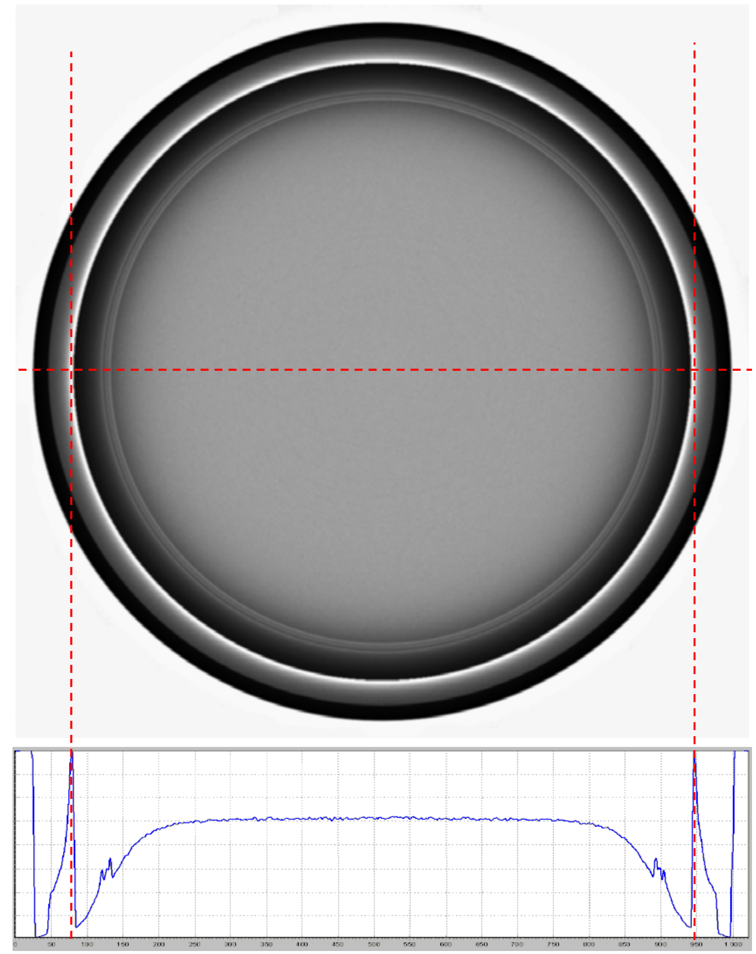
1. A **100-projections** visual-light micro-tomograph with a spatial resolution of ~1 um at λ~0.5 um
2. **3D Ray Tracing** code for numerical simulations of the images of multi-layer spherical shells.
3. The reverse algorithm **BBP** realizes the image element analysis (bright band parameters or **BBP**)

Results of preliminary analysis for BT-2 design

The bright band on the BT-2 shadow image can be used for precise control of the fuel layer NU and surface roughness using the developed reverse algorithm BBP.

Subjects for the next activity

1. Analysis for HiPER target with a porous layer (**BT-2a**)
2. Optical scheme optimization for both **BT-2** & **BT-2a**
3. Upgrading the tomograph developed at LPI to the required HiPER target standard.



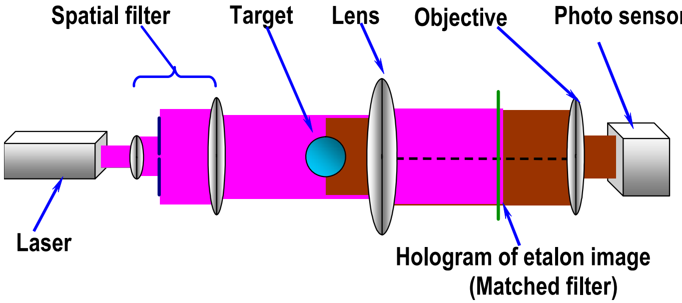
Simulated shadow image of **BT-2** (at Ap=60º) and intensity profile of the image.

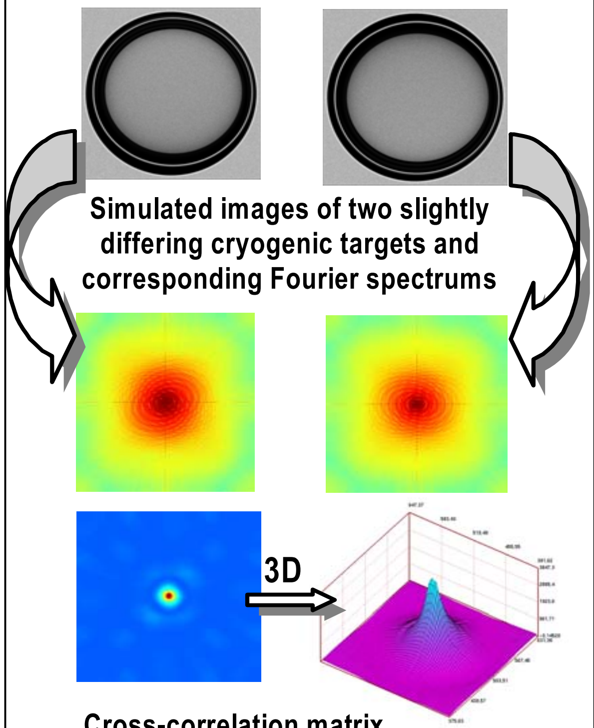
Numerical simulations made for 500 M rays using *3D Ray Tracing* code developed at LPI

Target parameters control (2): we consider Fourier holography of image recognition as a possible way to target *on-line* characterization

[E.R.Koresheva et al. Nuclear Fusion 2006]

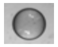
- The recognition signal is greater in the case of better conformity between the real and the etalon images
- The operation rate of such a scheme is several μsec

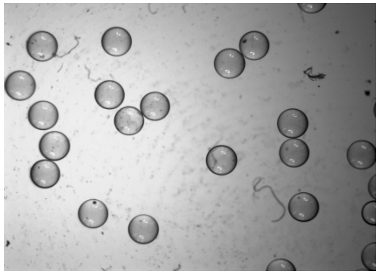




Simulated images of two slightly differing cryogenic targets and corresponding Fourier spectrums

Cross-correlation matrix of the images

 ← Etalon image



Studied image of the shells batch

Cross-correlation matrix of the studied and etalon images

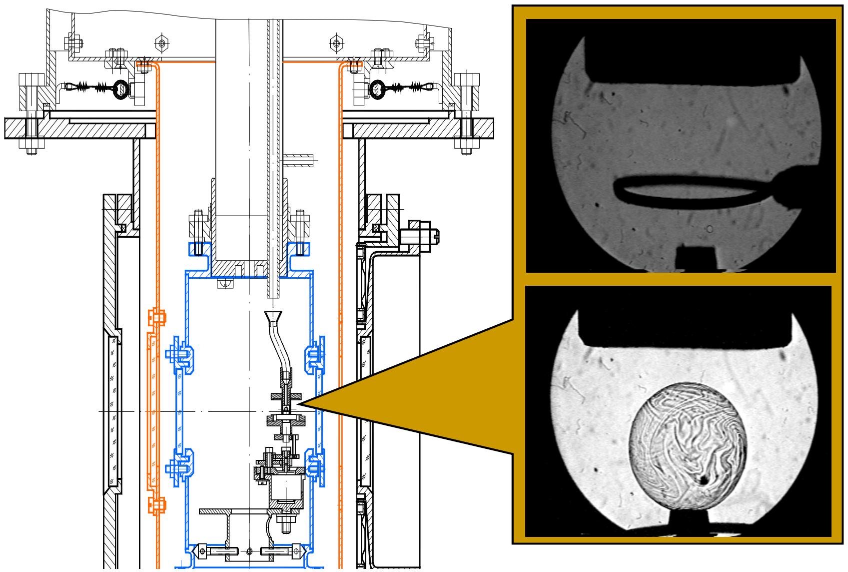
Computer experiments have demonstrated much promise of this approach for

- Recognition of the target imperfections in both low- and high- harmonics
- Quality control of both a single target and a target batch
- Simultaneous control of an injected target quality, its velocity and trajectory

Stage of characterization (3): Devices for free-standing target positioning inside TC

1-HOUR-MANIPULATION OF FREE-STANDING TARGET

(useful for target precise characterization)

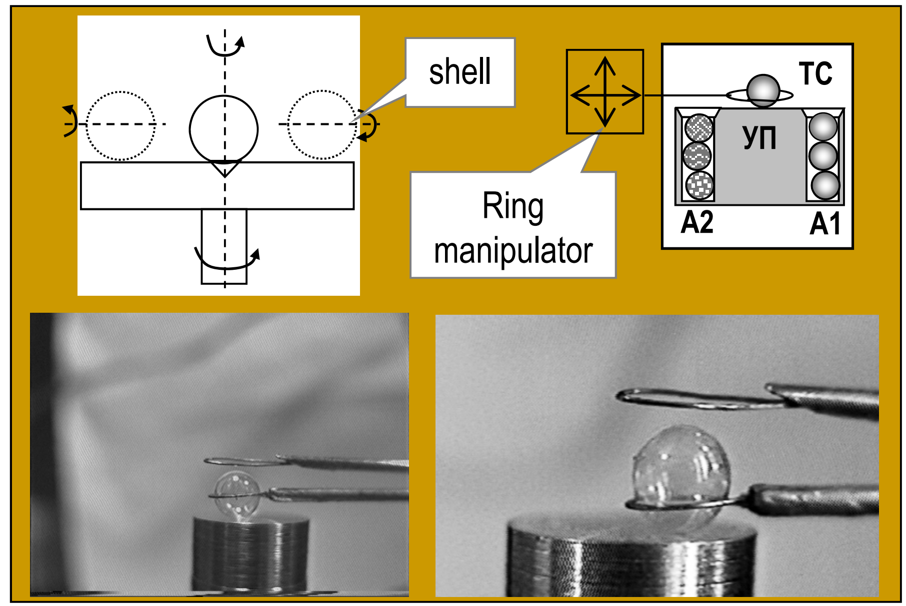


- ❑ Target positioning device (PD) is placed inside the TC of the layering module.
- ❑ The PD is used for accumulating up to 100 shadow projections of a target; full scanning angle 360^0, angle step 1.3^0
- ❑ Ring manipulator is used to align the target with respect to rotating axis.

Capacity for work has been demonstrated at T=5-20 K & 300 K

1-SEC-MANIPULATION OF FREE-STANDING TARGET

(useful for target on-line characterization)



- ❑ Mock-up testing has shown that the use of rotation disk allows having a comprehansive look at a target during several seconds
- ❑ Using the ring manipulator and according the results of target characterization the target can be rapidly delivered to the collector of high (A1) or poor (A2) quality targets

Capacity for work has been demonstrated at T=300 K

Subject for the next efforts: engineering a new FST layering module for examination of its work with HiPER-scaled targets in the single-step & rep-rate modes

---

Drawing of the FST layering module designed for production of fuel layer inside HiPER-class targets

Dimensions:

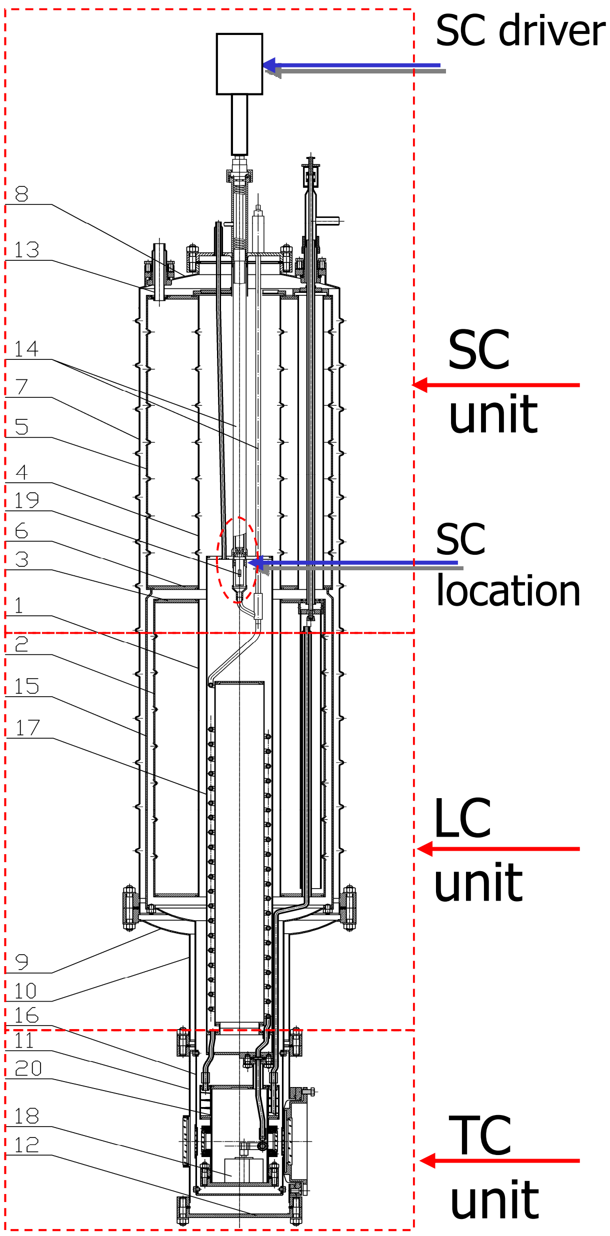
Height – 1.5 m

Diameter (max) – 45 cm

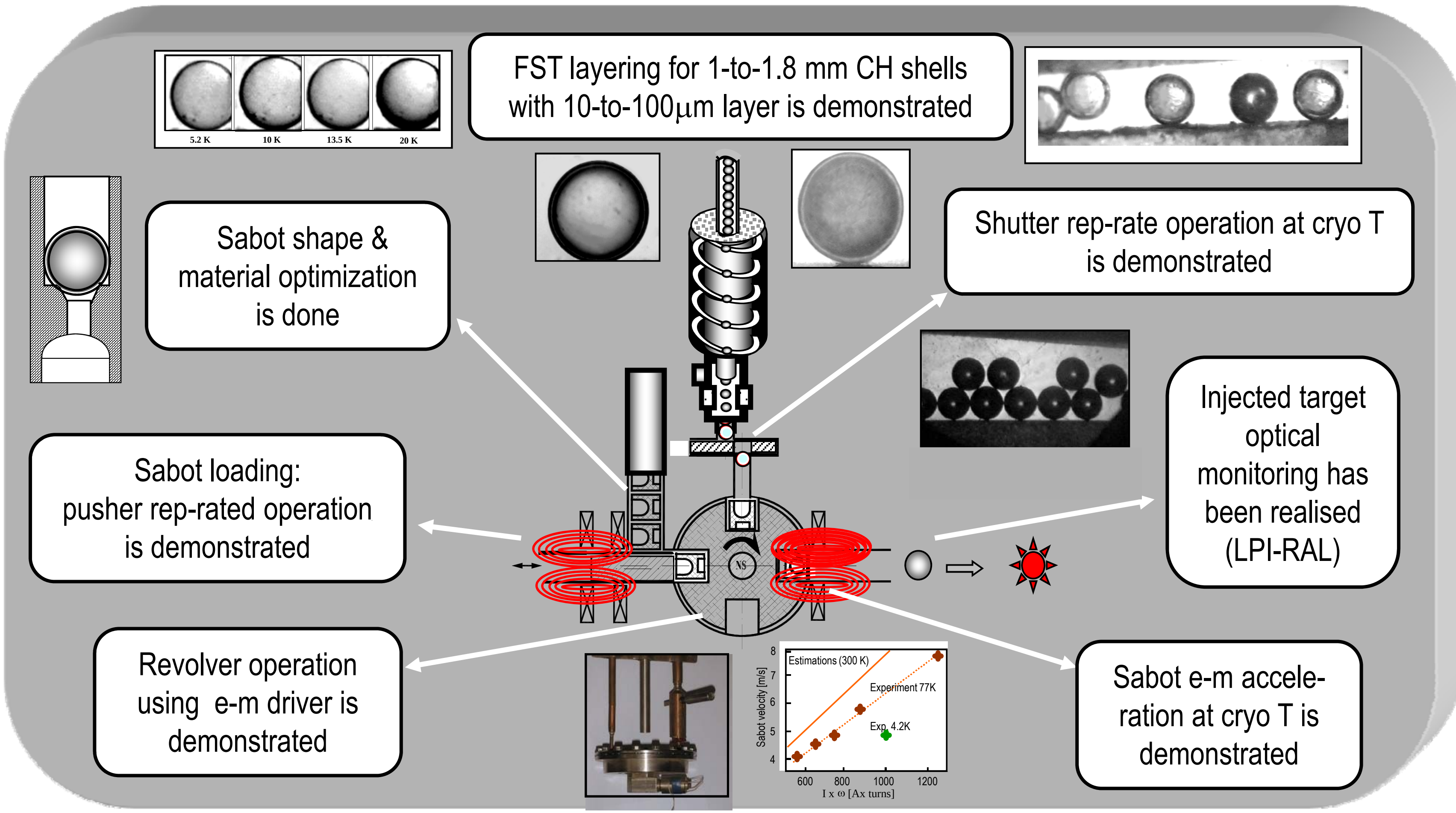
Liq. helium volume – 5 liters

Designed for:

- FST demonstration in a single-step mode
- FST demonstration in a high rep-rate mode (small batch of shells)



LM - injector connection via the device for target-&-sabot assembly: proposed & examined at LPI on a small scale (1 mm target; 10 mm-length sabot)



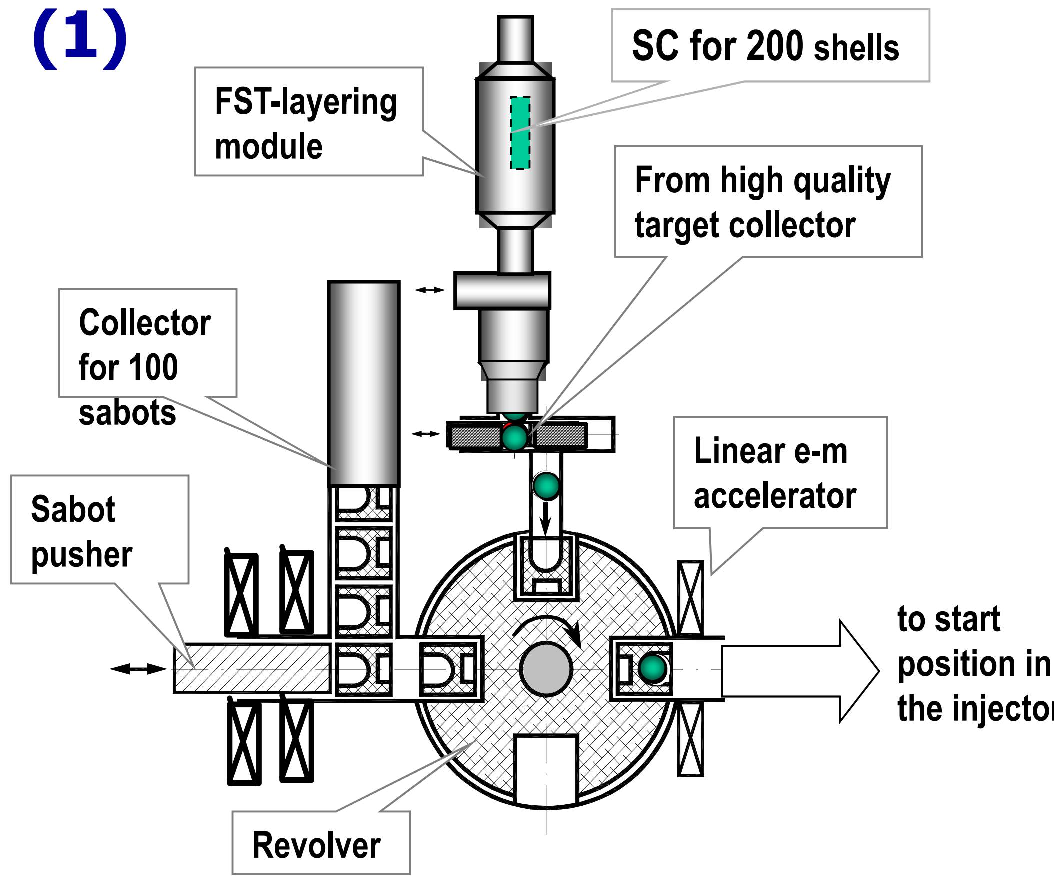
NEXT STEP: TO DEMONSTRATE THE SYSTEM OPERATION FOR HiPER-SCALED TARGETS

Schematic of a full-scaled FST system for a batch of 100 target-&-sabot units production to support the HiPER facility in a burst regime (100 shots per 1-to-10 sec). Dual - assembling mode.

Technical requirements

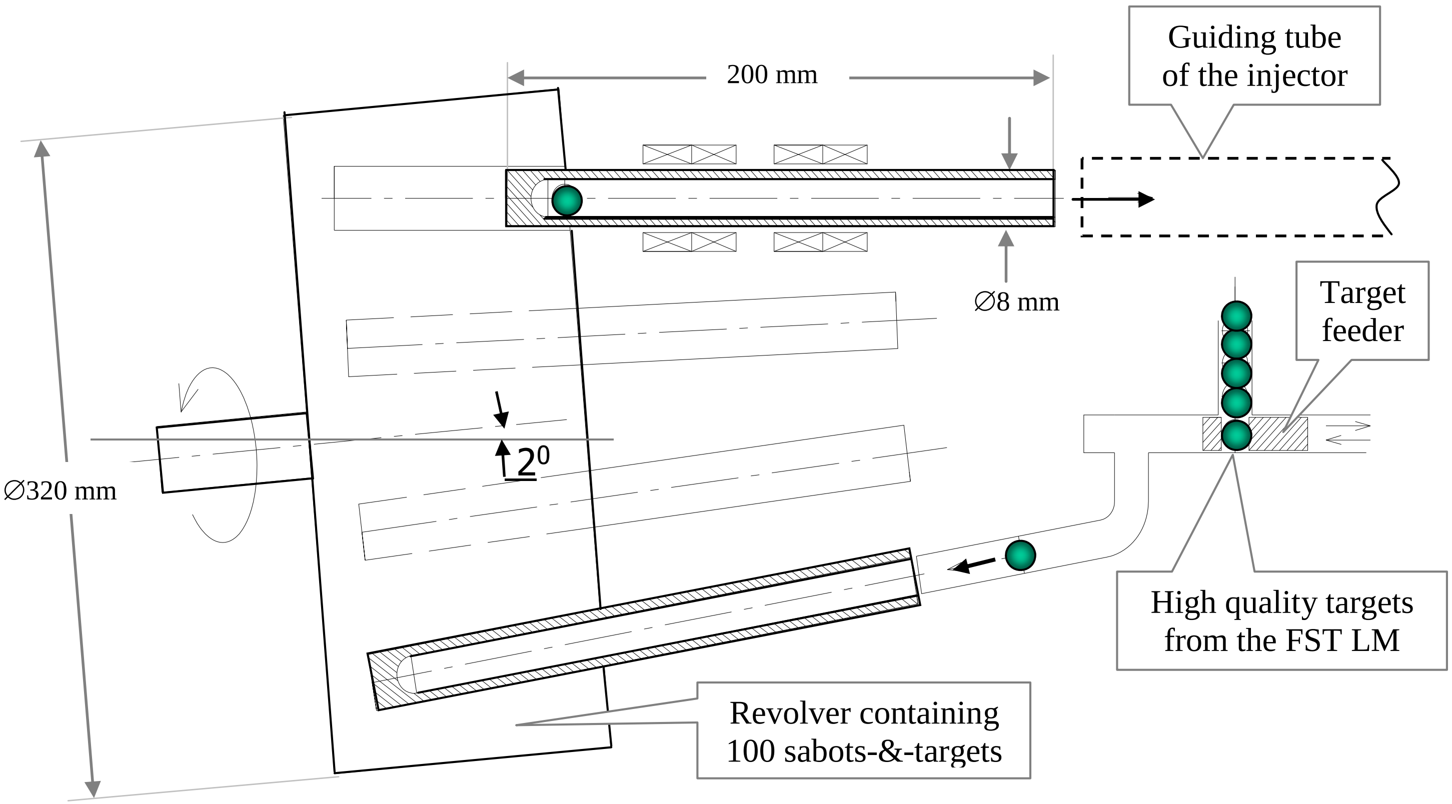
1. Shell container (SC) encloses 200 fuel filled shells
2. SC transport from fill system to LM goes at 300 K
3. Cryogenic layer formation by FST method
4. Sabot collector encloses 100 sabots
5. High quality cryo targets are injected under gravity into a device for target-&-sabot assembly
6. High rep-rate el.-m. delivery of the target-&-sabot units to a start position in the injector

(1)



100 shots per 1-to-10 sec

(2) Another option for the target-&-sabot assembly: collector of sabots and revolver as integrated packaging



Device for target-&-sabot assembly:
the revolver includes 100 target-&-sabot unit

100 shots per 1-to-10 sec

Open questions

- **The work performed at the ISTC Project #3927 has shown that**

1. Target materials are a key aspect for risk minimization in each FST-production step
2. For example, the following shell properties must be measured: tensile strength, elastic moduli, burst/buckle pressures, stress measurements (practically, all of them at room- and cryo- T); room- and low- temperatures permeability; thermal conductivity; radiation resistance, & etc.

- **STFC has sent 100 PAMS shells for mock ups testing in the frame of the ISTC Project #3927. Unfortunately, we have no reliable data on the PAMS shells properties at room- and cryo- temperatures.**

- **According the request of the Partner (M.Tolley, STFC), LPI has proposed a plan of the research into the unknown mechanical properties of the HiPER-class polymer shells** (using the existed at LPI facilities and methods), **including:**

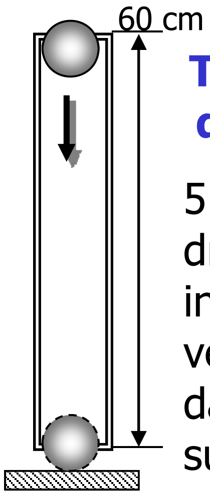
1. Measurement of external damage (backling) pressure at 300 K & cryo T
2. Measurement of internal damage pressure and calculation of tensile strength at 300 K & cryo T
3. Study of the effect of mechanical loads on the shell quality during fill process
4. Study of the effect of thermal and mechanical loads on the shell quality during FST process

Testing 10 PAMS shells has shown that the shells can be used for the FST production scheme in a new FST layering module. But, to minimize risk of target damage and optimize the FST production scheme, the mechanical properties of the shells must be measured.

Main parameters measured for 5 PAMS shells

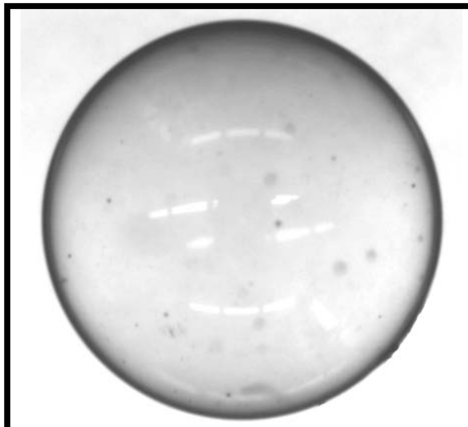
#	**Outer diameter, μm** (av. on 10 meas.)	**Weight, μg**	**Wall thickness** (av.), **μm**	**Buckle pressure at 300 K, atm**
1	**1813**	**217,4**	**19,8**	**28,5**
2	**1805**	**218,3**	**20,1**	**29,8**
3	**1804**	**223,0**	**20,6**	**28,2**
4	**1819**	**220,9**	**20,0**	**26,6**
5	**1821**	**210,6**	**19,0**	**25,2**

- Diameters of the shells were measured on an IMTsL-100x50A microscope (Novosibirsk, Russia); **accuracy ±0.2 μm**
- Weights of shells were measured using MXA 2/1-SensorDisplay analytical laboratory balance (Radwag, Poland); **accuracy ±0.1 μg**
- Buckle pressure was measured using the set up existed at LPI; **accuracy ± 0.1 atm**



Test on the risk of shell damage during its motion under gravity

5 of PAMS shells (N 6÷10) were droped down under the gravity inside a 60-cm-length (ID 5 mm) vertical tube. No one shell was damaged after its landing onto a substrate.



PAMS shell N6 after its landing
OD 1862 μm
Shell weight 231,3 μg
ΔR=19,8 μm

Current status of the FST technologies for HiPER-scaled cryogenic targets

- **LPI has proposed the FST technologies** for development of target facility, which operates at high rep-rate with cryogenic targets of a HiPER-class (target fabrication and delivery)
- **LPI has optimized the FST production scheme for HiPER project**: shells filling with fuel, shell container depressurization, FST layering inside moving free-standing shells
- **LPI has designed the FST layering module** (LM) for proper operation with HiPER-class targets. A set of mock ups has been built and tested, and a set of experiments were carried out in support of the FST LM design.
- **LPI has developed a conceptual design for the full-scaled FST system** that will ensure production of a batch of 100 target-&-sabot units to support a HiPER facility operation in a burst mode (100 shots per 1-to-10 sec).
- **LPI has proposed a plan of the research** into the unknown mechanical properties of the HiPER-scaled polymer shells (using facilities & methods existed at LPI)
- **LPI has tested 10 PAMS shells** given by the Partner (STFC/RAL); it was found:
  - the shells can be used for the FST production scheme using new FST LM
  - the unknown mechanical properties of the PAMS shells must be determined to optimize the FST production scheme and minimize the risk of shells damage

The work under way and subjects for future activity

- **The following work is under way in the frame of the ISTC Project #3927** (completion date: 30 April 2011):

1. Optimization of the layering channel geometry and temperature profile along its walls (which will allow using the shells from different materials and with different wall thickness)
2. Risk minimization associated with free-standing shells damage during their transport between the basic units of the FST layering module (calculations and mock ups testing).
3. Finalizing the draft design documentation for the FST layering module (D2 fuel)
4. Conditions for the FST layering module operation with radioactive DT-fuel
5. Information retrieval on the product-producing companies and prices of the necessary standard elements

- **Subjects for future activity:**

1. FST layering module: development of working drawings and manufacture
2. Determination of the adaptation level and upgrade of the fill system and characterization system (existed in LPI) for operation with HiPER– scaled targets
3. Experimental examination of work of the FST layering module with the HiPER-scaled targets (single-step & rep-rate operation)