Target Fabrication Activities in Collaboration of Moscow Institutes

Yu.A. Merkul'ev
Thermonuclear Target laboratory of
Lebedev Physical Institute, Moscow, Russia

I.V. Akimova, A.A. Akunets, I.V. Aleksandrova, G.D. Baranov[1], N.G. Borisenko, E.R. Koresheva, A.A. Belolipetskiy[2], V.A. Bobrov[3], V.S. Bushuev, V.V. Gorlevskiy[3], A.I. Gromov, E.L. Koshelev, A.I. Kupriyashin, B.V.Kuteev[4], V.I. Listratov[1], Yu.E.Markushkin[3], A.I. Nikitenko, A. M. Oparin[5], I.E. Osipov, V.G. Piminov[7], E.E. Sheveleva[7], M.S. Sheverdyaev[3], P.A.Storozhenko[8], I.D. Timofeev[1], T.P. Timosheva, S.M. Tolokonnikov, G.S. Usachev[1], L.S. Yaguzinskiy[6], A.V. Zabrodin[3].

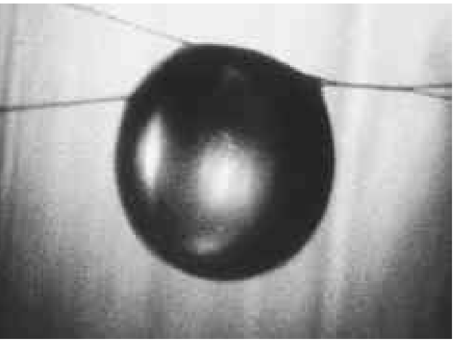
Lebedev Physical Institute, Moscow, Russia
[1]Red Star State Enterprise, Moscow, Russia
[2]A.A.Dorodnitsin Computing Center of RAS, Moscow, Russia
[3]Bochvar Institute of Inorganic Materials, Moscow, Russia
[4]Institute of Nuclear Fusion, RRC "Kurchatov Institute", Moscow, Russia
[5]Institute of Computer Aided Design of RAS, Moscow, Russia
[6]Institute of Physics-Chemical Biology, Moscow State University, Moscow, Russia
[7]N. D. Zelinsky Institute of Organic Chemistry, Moscow, Russia
[8]GNIICHTEOS, 38 Shosse Entusiastov, 111123, Moscow, Russia

3rd Moscow Meeting on Targets & Application 15-19 October, 2007, Moscow

Outline

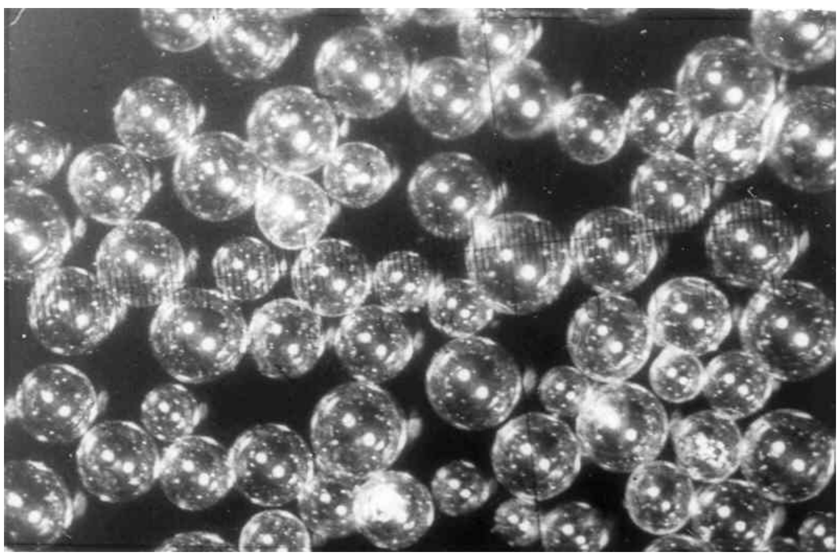
- Introduction. Several words about joint works of Thermonuclear Target Laboratory (TTL) LPI with the Russian Institutes and foreign Centers.
- Novel results during past 5 years.
- Our targets in laser experiments.
- Application of our technologies.
- Conclusion.

Laser target group in LPI began to work at 1974.
The first results (1975) of our group in LPI



Solid spheres from deuterium

Target group of LPI at 1977→



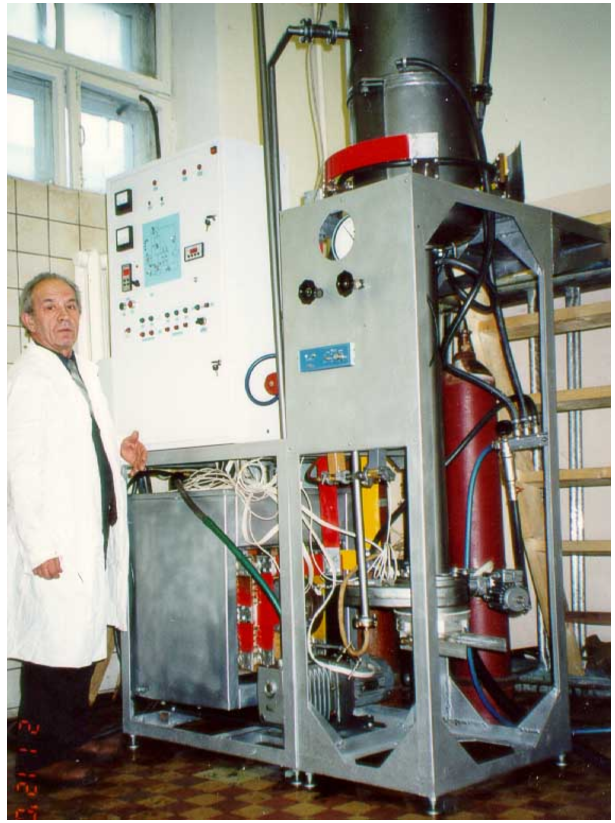
First shells from polystyrene, 1974

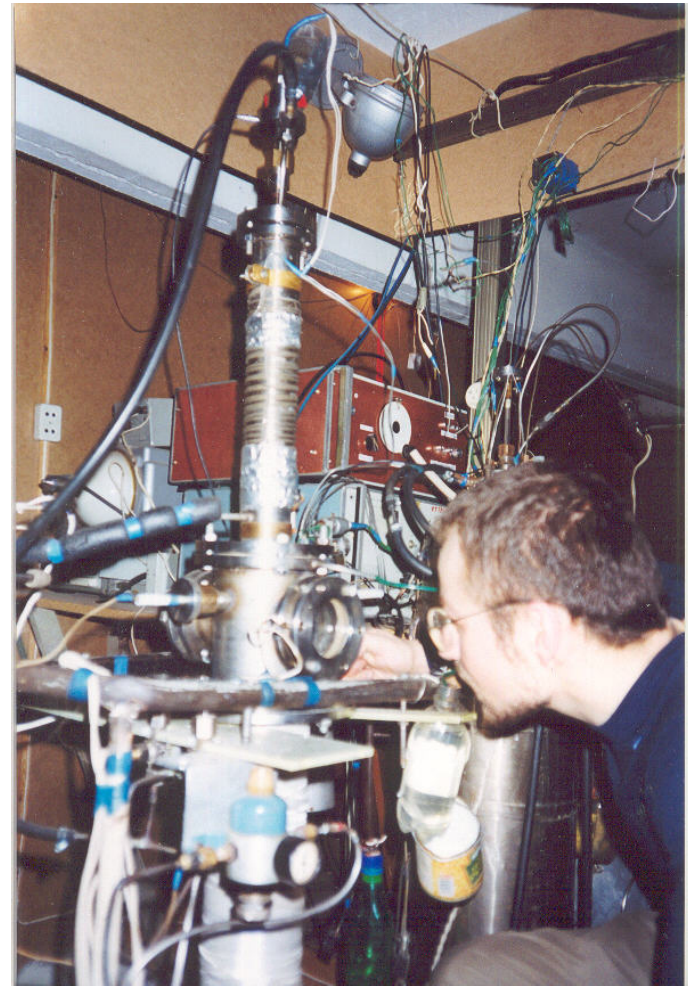
Our first results had been presented on XII ECLIM in Poland at 1975

Introduction. Several words about joint works of Thermonuclear Target Laboratory (TTL) LPI with the Russian Institutes and foreign Centers.

- Our group produced different targets for “Kalmar” and “Delfin” lasers and created technological instellations and apparatus for characterization of targets.
- We fabricated shell-targets beginning from substances up to capsules filled DT-mixture (for example, for RAL, UK at 1988-1992) and we created DT-gas filling system upto 200 bar, but we could not work with tritium in Moscow center.
- Our laboratory had designed and had partically created the equipment complex for target production for 12 kJ, 60 kJ and 200-300 kJ laser.
- Novel equipment carry out with automatic computer control.
- Equipment and software developed in LPI and our laser targets were used in 7 Russian Institutes and in 8 Scientific Centers in 7 countries.
- A lot of our project works were fulfilled at support by International Science and Technology Center, by direct contracts between Institutes, by European grants or personal participations in European projects.

Equipment for the scientific centers in foreign countries in the years 1997-2002

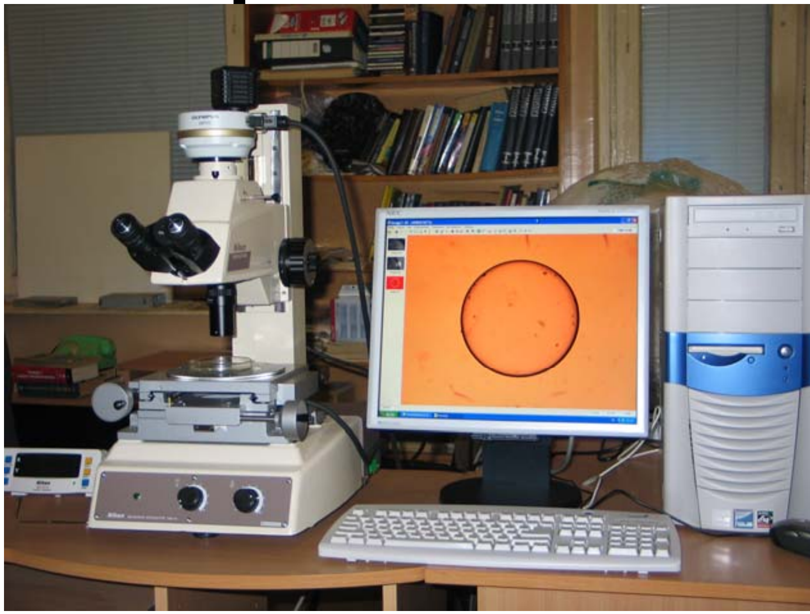


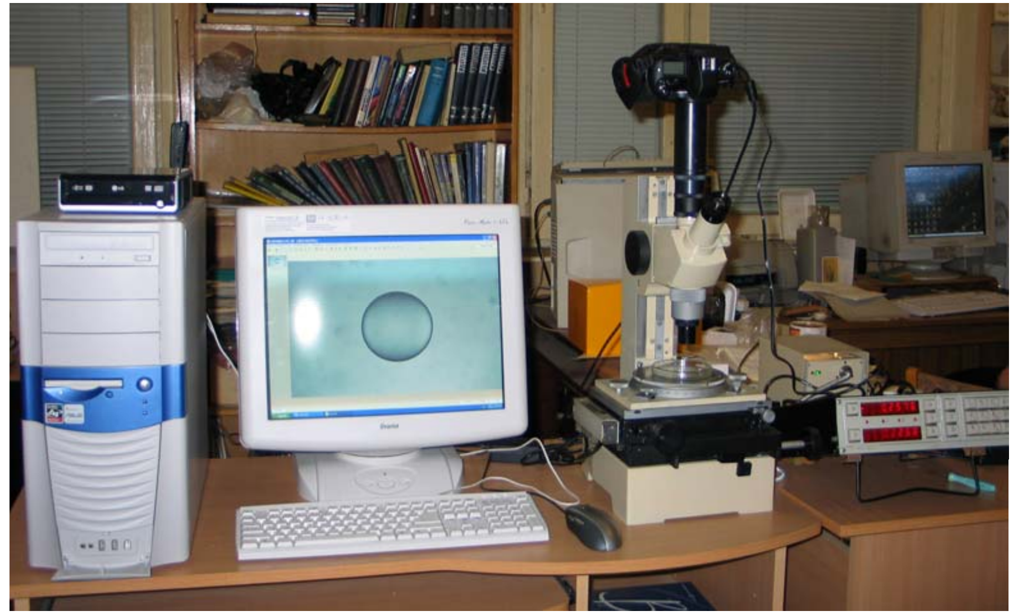


The installations produced by LPI for glass and plastic shell target. Now equipment carry out with automatic computer control

High-temperature droplet generator for concentrated (50%) silicate solution. (V.M. Dorogotovtsev poster)

Optical and x-ray shell characterization



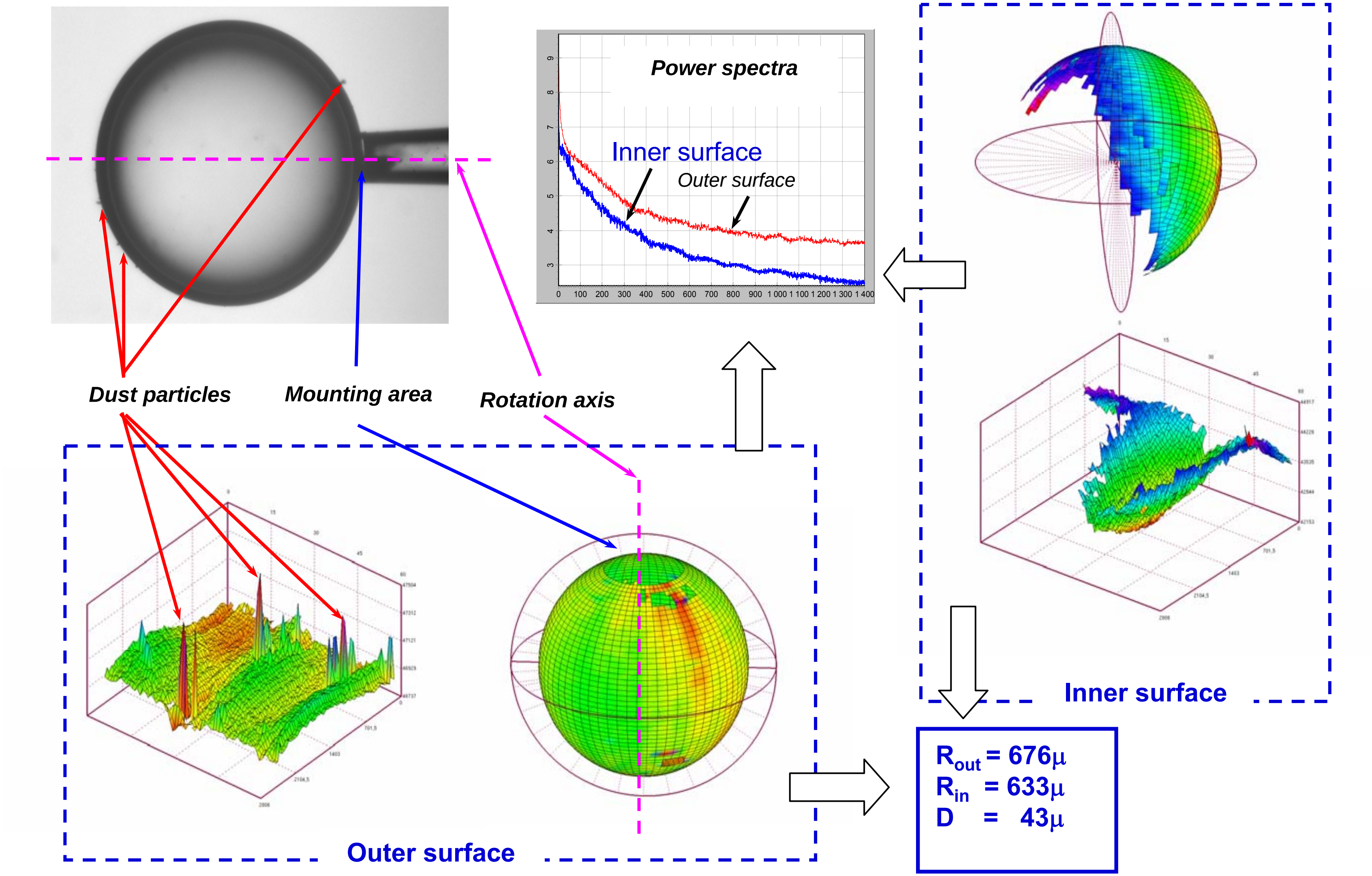


Two automatic optical systems with high resolution CCD-camera and original software for shell characterization. Made in LPI and delivered to different Russian Institutes. Software had been written using ray-tracing method in 2001. Now it also includes wave-let analysis of 100 – 200 images for single or double-layer shell.

Andrey I.Nikitenko et al. & Sergey M. Tolokonnikov et al. Oral talks on MW TA 2007

Koresheva E. R., Nikitenko A.I et al. Possible approaches to fast quality control of IFE targets Nucl. Fusion **46** (2006)

A.I.Nikitenko et al. MP15 Report on Target Fabrication Meeting 1-5 October, 2006, San Diego, CA, USA; Nucl. Fusion **47** (2007)



ICF target characterization. Inner and outer surfaces reconstruction from the set of shells' shadowgraph projections. Single-layered shell.

A.I.Nikitenko et al. Nucl. Fusion **47** (2007 MP15 Report on Target Fabrication Meeting 1-5 October, 2006, San Diego, CA, USA; **Sergey Tolokonnikov talk on MW TA 2007**

Requirements to direct (indirect) polymer cryogenic targets for laser with energy 300 kJ

№	Parameter	Value	Accuracy	Deviation
1	Shell mass m_{targ} , mg	1.1– 1.7 (0.4-0.75)	0.01	0.03 (0.02)
2	Mass DT, m_{DT}, μg	25 – 100 (15-150)	0.5	1 (0.5)
3	Pressure, atm.	40– 350 (60– 400)	1 (3)	3 (10)
4	Shell diameter, mm	2.2 – 2.8 (1.6-2.3)	0.5 μm	2 μm (1 μm)
5	Wall thickness, μm	16 – 35 (25 – 70)	0.05	0.2 (0.5)
6	Thickness variation, %	0.3-0.5 (0.3-0.5)	0.1	0.2 (0.3)
7	Surface roughness, μm	0.02-0.04 (0.02-0.03)	0.01	0.02
8	Thickness of DT-layer, μm	15-40 (12-40)	1	1.5-3 (2-5)
9	Variation of DT-layer thickness, %	1.2-2 (2)	0.5	1.5 (1)
10	Roughness of inner surface of DT-layer, μm	0.3-0.5	0.1	0.3
11	Temperature, K	4.2-12 (7-15)	0.05 (0.01)	0.3 (0.01)

Basic direct target constructions for laser with energy about 0.5 MJ

- Be, C or polymer capsules (Ø1.6-2.8) with cryo-DT-layers and fast ignition from one side (ignition is unlikely). (1-4)
- Similar capsules with cone for fast ignition (high compression is unlikely). (2)
- Double shells targets without cryogenics. (2)
- Foam polymer shells (wetted foam or all-DT targets) with cryo-DT-layer are perspective for fast ignition from one side. (4)
- May be. Capsule from substances with high concentration of heavy isotopes of hydrogen as variants of “All-DT targets” with cryo-DT-layers and fast ignition from one side. This targets also are perspective for fast ignition from one side. (1-3)

Comparison of large capsule fabrication methods

1. Fabrication of polymer and glass shells (only up to Ø1.6-2.4) in drop tower furnace
2. Production hemispheres shell by tools.
3. Production hemispheres shell by coating mandrels by vapor deposition.
4. Microencapsulation for polymer shell or polymer foam production

Five-stage method of large glass shell-target fabrication

1. large silicate monodisperse granules production in high-temperature droplet generator for concentrated silicate solution,
2. drying granules in drop tower hot tube and the following cooling in liquid nitrogen,
3. freeze-drying of silicate granules,
4. large glass shell formation in high-temperature vacuum drop tower furnace,
5. repeated blowing up of glass shells filled hydrogen in vacuum drop tower furnace for glass shells >2mm production.

Merkuliev Yu.A. The Fundamentals of Hollow Microspheres-Microballoons Technology. // Laser Thermonuclear Targets and Superdurable Microballoons. Edited by A.I. Isakov, Nova Science Publishers, Inc., 1996, p. 141-230.

Dorogotovtsev V.M., Chirin N.A., Gorlevsky V.V., et al. Research of possibility of target fabrication from beryllium deuteride (foaming technique). // Proceedings of SPIE 2001, Vol. 4424, pp. 159-162.

The installation for fabrication of initial granules from concentrate alkaline silicate glass solution

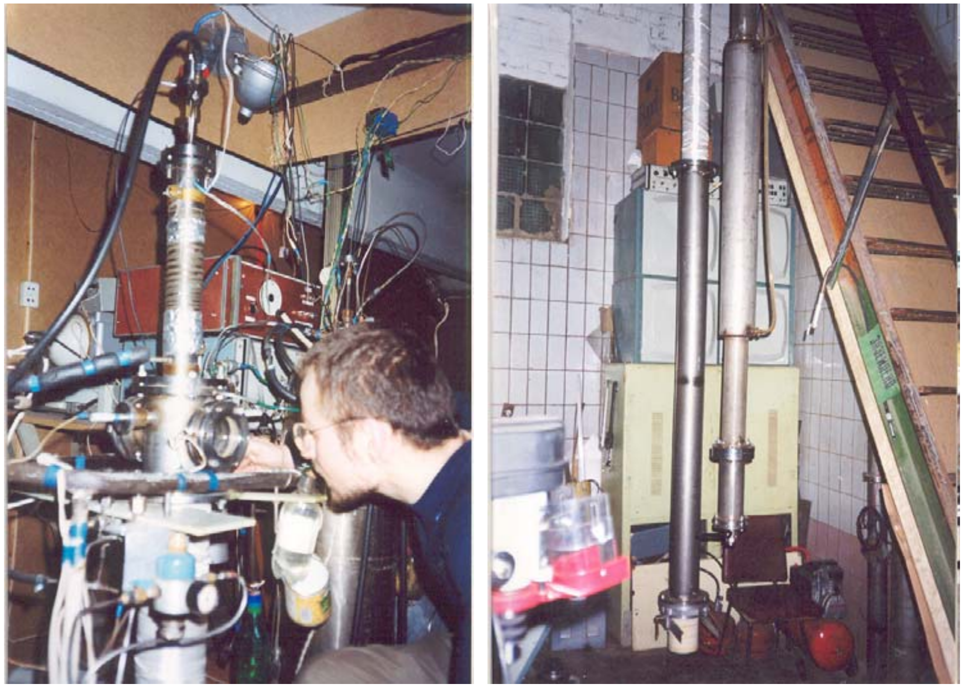
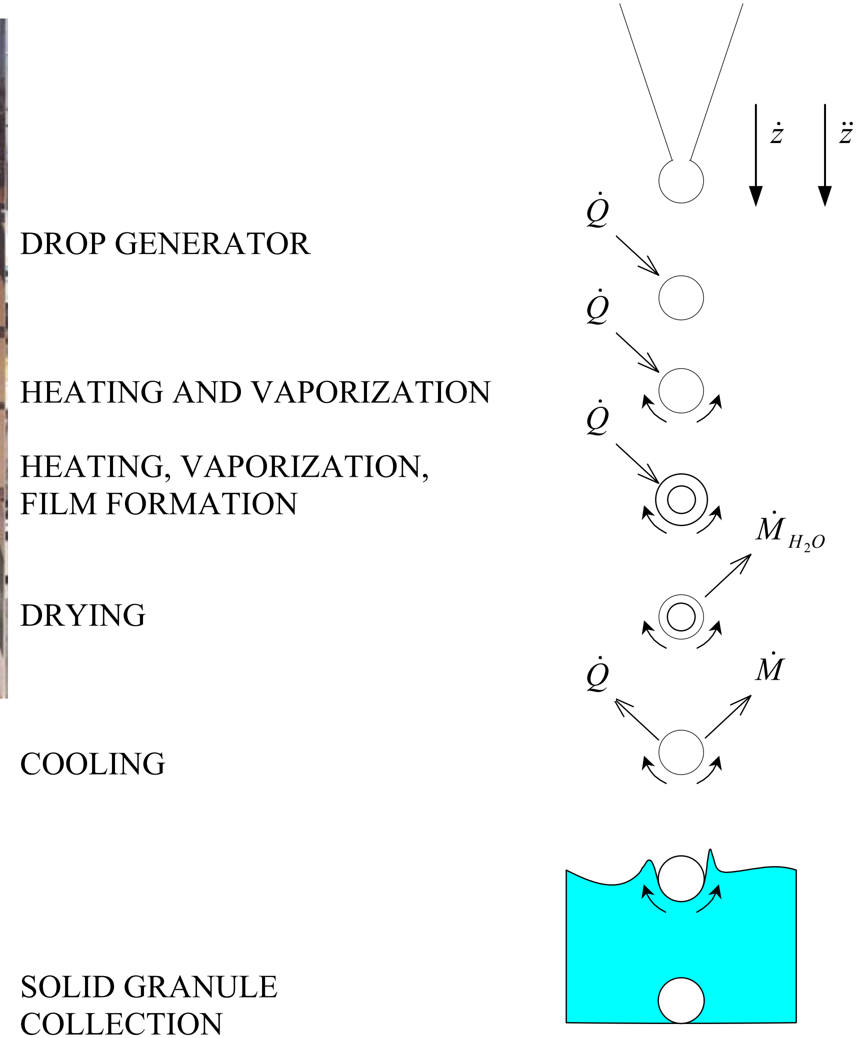


Photo of the droplet generator (1st stage) for the concentrate alkaline silicate solution with drying drop tower hot tube (2 stage) and cooling in N_2-liquid vessel.



Sequence of physical processes in fabrication of the alkaline silicate particles from the concentrated silicate solution

•Merkuliev Yu.A. // Mater. Res. Soc. Proceedings, 1994, **v. 372**, pp. 283-288.

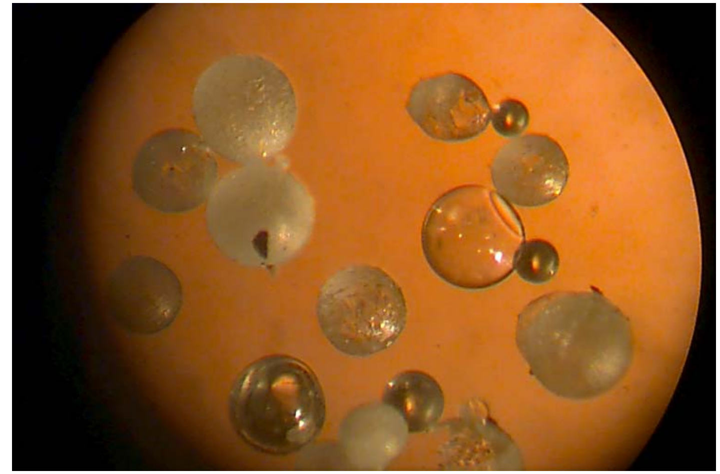
•Hendricks C. D., Walsh T., Motta B. // J. Moscow Phys. Soc. **V. 8**, (1998), pp. 171-176. Dorogotovtsev V.M. poster on MWTA

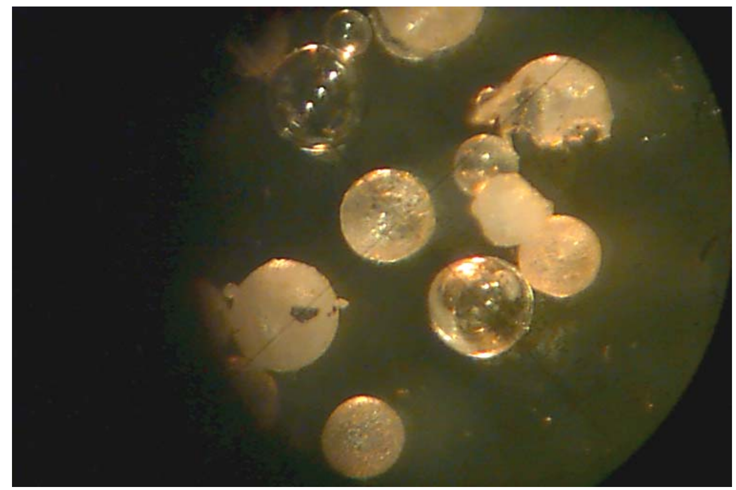
Drop tower furnace for BeD_2 shells fabrication.

←Automatic vacuum drop tower furnace with 3 hot zones for formation of BeD_2 and $LiBeD_3$ shells (up to Ø 0.5 mm) with lock and vessel in which targets are transposed in vacuum to the laser chamber.

TTL of LPI, 2003.

Now in Bochvar Institute.



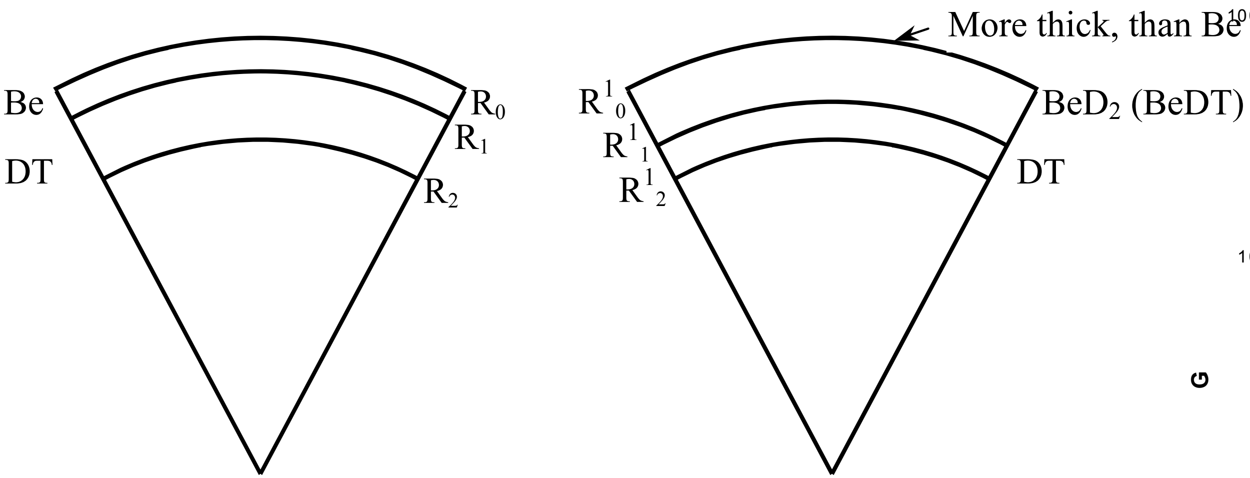


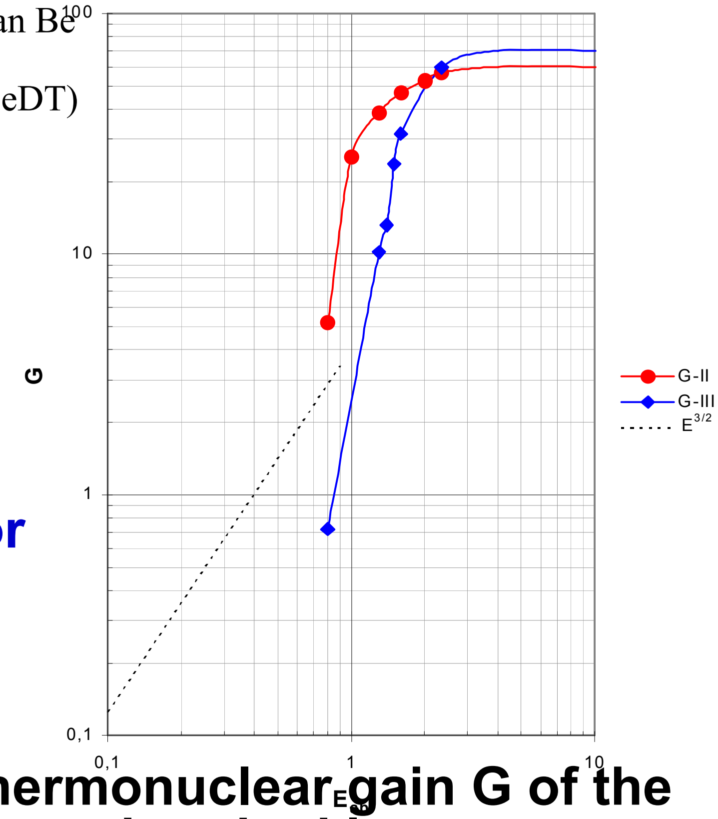
First shells from NH_3BH_3, fabricated in TTL on 14.04.03.

Some are optical transparent

Yu.A.Merkuliev, et al. Laser targets from new solid materials with high concentration of hydrogen isotopes for neutron generation. // Journal de Physique IV (France), June 2006, Vol. 133, pp. 887-890.

THE ENERGETIC EFFICIENCY OF LASER THERMONUCLEAR TARGETS WITH SHELL-ABLATORS MADE OF BERYLLIUM MATERIALS.





The target with a low-aspect-ratio shell-ablator made of beryllium deuteride, which better resists the growth of the hydrodynamic instability and provides higher gain factors at the absorbed laser energy about 1.5÷2 MJ.

The increased gain in BeDT target in comparison with shell of BeH_2 is due to wall burn

Dependences of thermonuclear gain G of the BeD_2-shell-targets on absorbed laser energy Eab for the two sequences of numerical simulations made for different ratio of the ablator mass and fuel mass: G-II – M_{ab}/M_{DT} =3.7 and G-III - M_{ab}/M_{DT} =4.6.

S.Yu. Gus'kov, N.V. Zmitrenko, Yu.E.Markushkin, Yu.A. Merkuliev. Journal of Russian Laser Research. 2007, Vol. 28, No 2, pp. 148-162 (Preprint #20, Lebedev Physical Institute, 2001, 24 p.)

Properties of solid hydrides of light elements

Material	$LiBeD_3$	$LiBD_4$	BeD_2	$(CD_2)_n$	ND_3BD_3
Density, g/cm^3	≈0.83	≈0.86	0.765	1.10	0.92
Number $\Sigma(Z_i+1)$ to 4 (number D_2)	2.5	2.25	2.25	2.75	2.167
Module of elasticity, GPa			27.3	3.4	
Melting point, °C (Glassy temperature),			140 (134)		106
Boiling point, °C (Temperature of momentary disintegration)			(≈350)	(≈520)	(≈300)
Permeability for H_2, cm^2/atm.s,			$<5\cdot10^{-12}$	10^{-6}	$\approx<10^{-9}$
Optical transparency (<0,1 mm)	semi	yes	yes	yes	yes
Surface roughness, nm			<10	<60	<30
Structure (crystal, amorphous)	crys.	crys.	amor.	am-cr	crys-am

GNIIChTEOS specialists have been producing ND_3BD_3 since December 2004.

Dr. Yu.E. Markushkin with assistants fulfilled isotope exchange in ammonia-borane. In 6 hours 8 at% of H_2 was substituted for D_2

Yu.A.Merkuliev et al. Proceedings of SPIE 2001, Vol. 4424, pp. 139-143.

Yu.E. Markushkin, A.A. Akunets, N.G. Borisenko, et al. Beryllium and Lithium Deuterides in Direct and Indirect Laser Targets. // Inert. Fus. Sci. and Appl. Elsevier, Paris, 2002, p. 772-776.

Solid materials with high concentration of hydrogen isotopes

Materials with high content of deuterium (for example LiD, BeD_2, $LiBeD_3$, $LiBD_4$ or ND_3BD_3) or T-containing materials can be used for large (reactor-scale) fusion target instead of beryllium or polyimide. The burning reactor-size targets are shown to be profitable [1] as regards energy yield. Possible methods of large fusion target fabrication for high power lasers are discussed both for direct and indirect schemes [1, 2]. It is the alternative to the burning target called "wetted foam" or "All DT" [3] (of the type: $CH(DT)_4$ or $CH(DT)_{64}$).

Shells from BeDT or NT_3BD_3 can be surrogate of cryogenic targets in experiments with large-scale lasers [4], Z-pinches or heavy ion drivers, when expensive DT cryogenic systems are not yet installed in interaction chamber. The targets of these materials are also used in the neutron generation research in super high intensity laser fields [5]. Low-density BeD_2 or $LiBeD_3$ foams layers can be used as absorbers of laser radiation and for fast heat transfer onto shell-target [6].

1. S.Yu. Gus'kov, Yu.E. Markushkin, Yu.A. Merkul'ev, N.V. Zmitrenko, J. Rus. Laser Res., 2007, V.28, #1 (LPI preprint, 2001, #20, 24 p.)
2. S.A. Belkov et al. Quantum Electronics (Russian), 2002, V. 32, No 1, p. 27.
3. S.E. Bodner, D.E. Colombant, A.J. Schmitt, M. Klapisch. Physics of plasmas, (2000), Vol. 7, No 6, 2298
4. Yu.E. Markushkin, et al. Inertial Fusion Sciences and Applications. Elsevier, Paris, 2002, pp. 772-776.
5. V.S.Belyaev, et al. Journal de Physique IV (France), June 2006, Vol. 133, pp. 507-509.
6. N.G. Borisenko, et al. Journal de Physique IV (France), June 2006, Vol. 133, pp. 305-308.

Automatic precise D_2-filling system for polymer and glass shells up to 120 MPa.

Two step D_2-filling system lifts pressure in the filling chamber with special targets cassette

First step: ZrFeCr – D_2 SOURCE - SORPSION COMPRESSOR P≤20MPa T=250-350^{o}C FILLING SHELL PRESSURE – 35 MPa COMPUTER CONTROLLED FILLING PROCEDURE

Second step: thermocompression

FILLING CHAMBER P≤ 200MPa, T=350-400^{o}C HIGH ACCURACY COMPRESSOR ΔP~0.1-0.2%

The system was created in LPI for VNIIEF in 2005

Andrey Nikitenko et al. talk on MW TA 2007

TARGET SYSTEM OPERATION IS BASED ON THE FREE-STANDING TARGET (FST) TECHNOLOGIES DEVELOPED in LEBEDEV PHYSICAL INSTITUTE

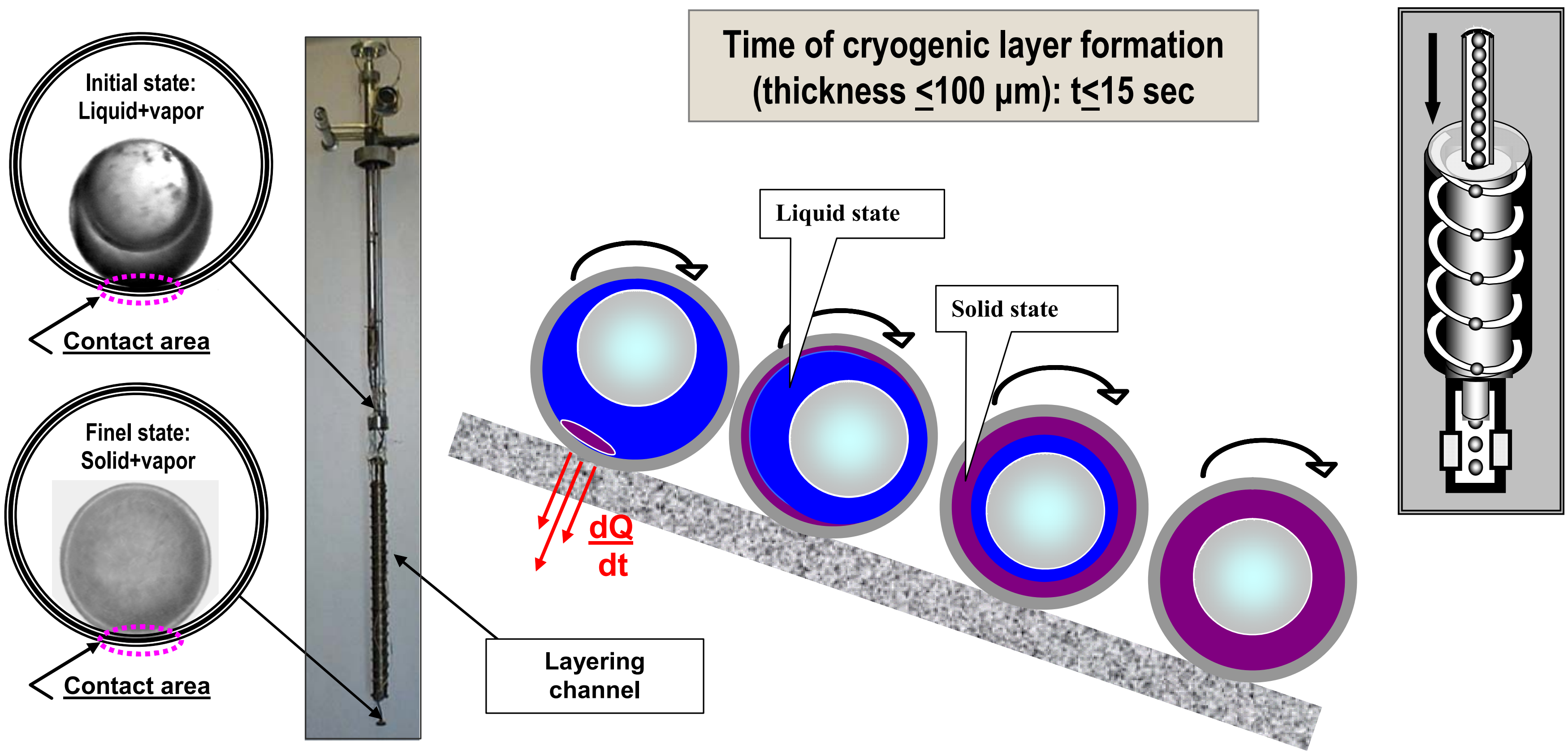
[E.R.Koresheva et al. J.Phys.D: Appl.Phys.**35**,2002; Fusion Sci.&Tech.**43**,N3,2003; Laser&Part.Beams,**23**,2005]

CRYOGENIC LAYER FORMATION USING THE COMBINED FST-LAYERING METHOD:

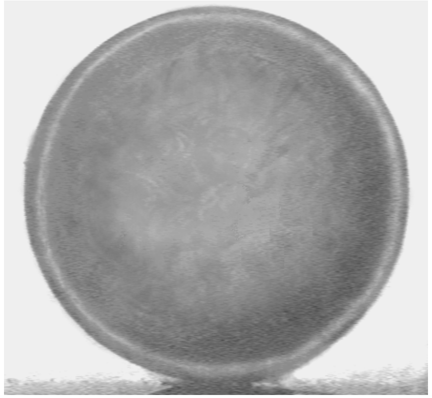
(1) Fuel cooling due to heat removal through the target / channel wall contact area

(2) Fuel layer simmetrization due to random rotation of a target

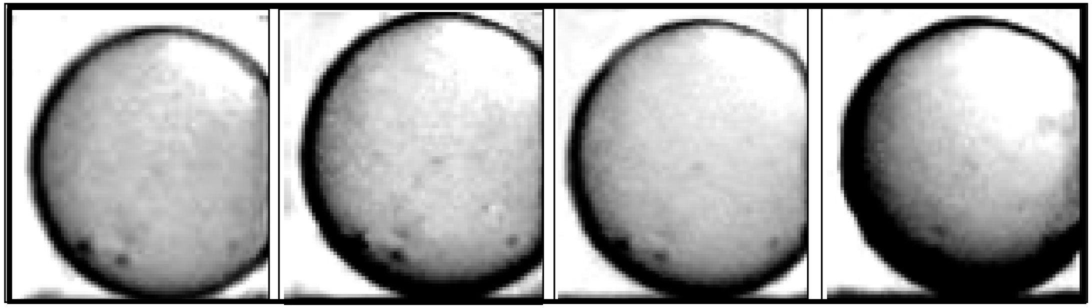
(3) Cryogenic fuel layer formation in an isotropic high dispersity (or amorphous) state and its stabilization due to application of a dopant from heavy hydrogen isotopes (or another material)



COMBINED FST-LAYERING: FUEL LAYER SIMMETRIZATION, COOLING AND AMORPHYSATION. It has been demonstrated experimentally that using a certain doping allows to form transparent thermo stable spherically-symmetric D_2 – layer inside moving free-standing shells



Cryogenic layer formed using the combined FST-layering



5.2 K **10 K** **13.5 K** **20 K**

Transparent solid cryogenic layer does not spoil in the wide range of temperatures from 5 K up to the triple point

TARGET PARAMETERS

Polystyrene shell: ∅ =1500 mcm
Shell thickness: 20 mcm
Outer coating: 200 Å Pt/Pd
Fill pressure (300 K): ~270 atm
Gas density (300 K): ~38 mg/cm3
Cryolayer material: 80%D_2+3%Ne
Cryolayer thickness: 50 mcm

EXPERIMENTAL CONDITIONS

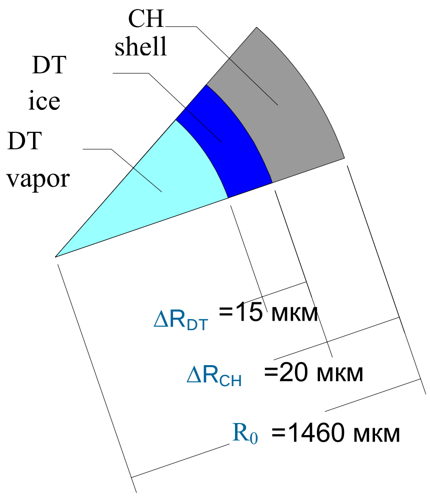
Spiral channel: L=1.5 m ID =2600 mcm
T_{IN} (target input temperature): 31 K
T of the test chamber bottom: 5 K
Pressure inside the channel: 1 mtorr
Time of target residence inside the channel: 10 сек

CALCULATED PARAMETERS

$\chi=S/4\pi R^2$	τ, sec	q, K/sec
0.035	1.57	7.9

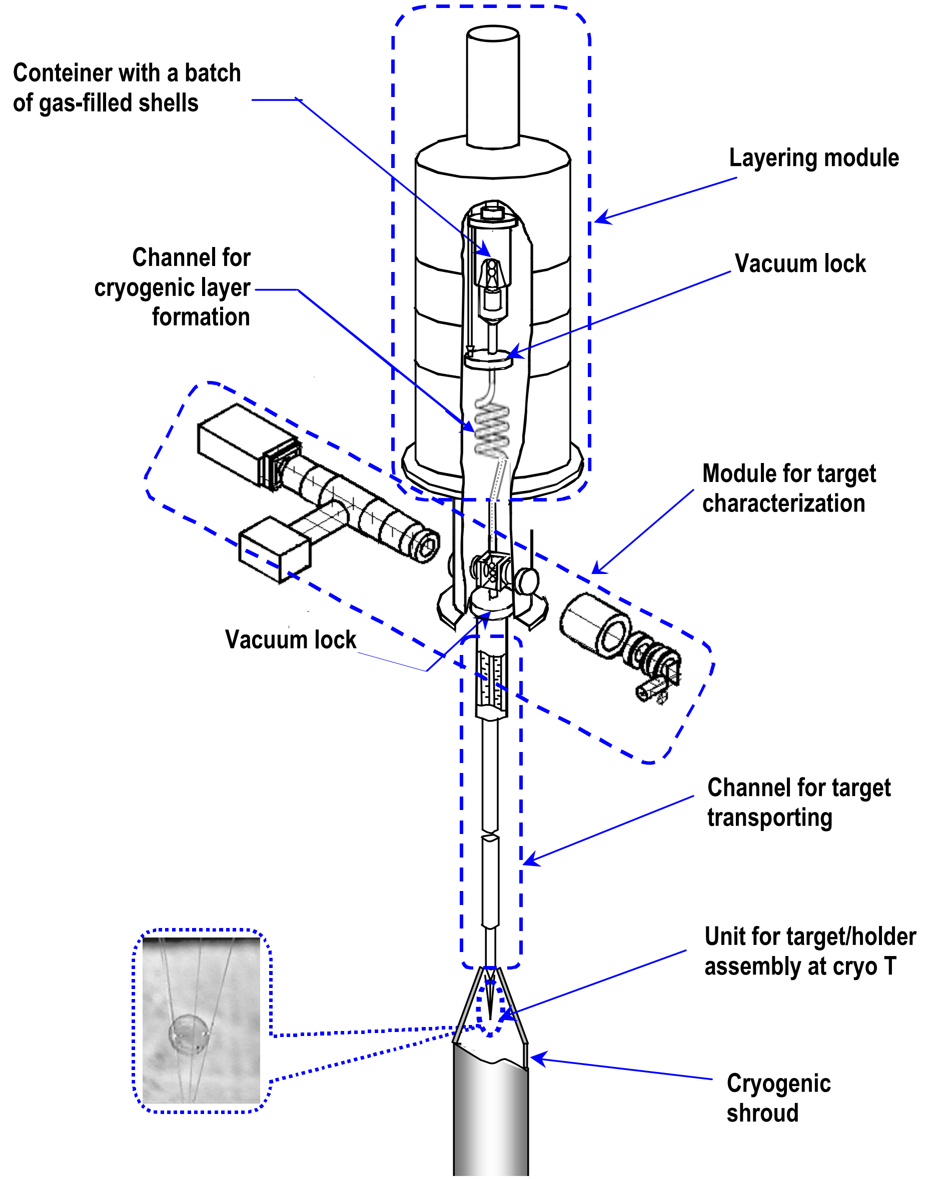
E.R.Koresheva et al. Fusion Science and Thechn. **47**, 2007. Report on Target Fabrication Meeting 1-5 October, 2006, San Diego, USA

OPTIMAL DIRECT-DRIVE TARGET FOR LASER FACILITY (300÷500 кДж). TARGET SYSTEM FOR CRYOGENIC TARGET FABRICATION AND DELIVERY INTO THE CENTER OF TARGET CHAMBER



Parameters of laser radiation	Target parameters [1]	
Input Energy - 300 kJ Wave length - 0.351 mcm Pulse duration - 8.5 nsec	1.Mass of DT	0.1 mg
	2.ΔR_{DT}	15 mcm
	3.R_0	1.46 mm
	4.ΔR_{CH}	20 mcm
	5.ρ (DT-vapor)	$5 \cdot 10^{-4}$ g/cm^3
	6.T (DT-layer)	~19.6 K
	7.Fill pressure (300K)	42 atm
Input Energy - 500 kJ Wave length - 0.351 mcm Pulse duration - 8.5 nsec	1.Mass of DT	0.171 mg
	2.ΔR_{DT}	23 mcm
	3.R_0	1.54 mm
	4.ΔR_{CH}	33 mcm
	5.ρ (DT-vapor)	$5 \cdot 10^{-4}$ g/cm^3
	6.T (DT-layer)	~19.6 K
	7.Fill pressure (300K)	60 atm

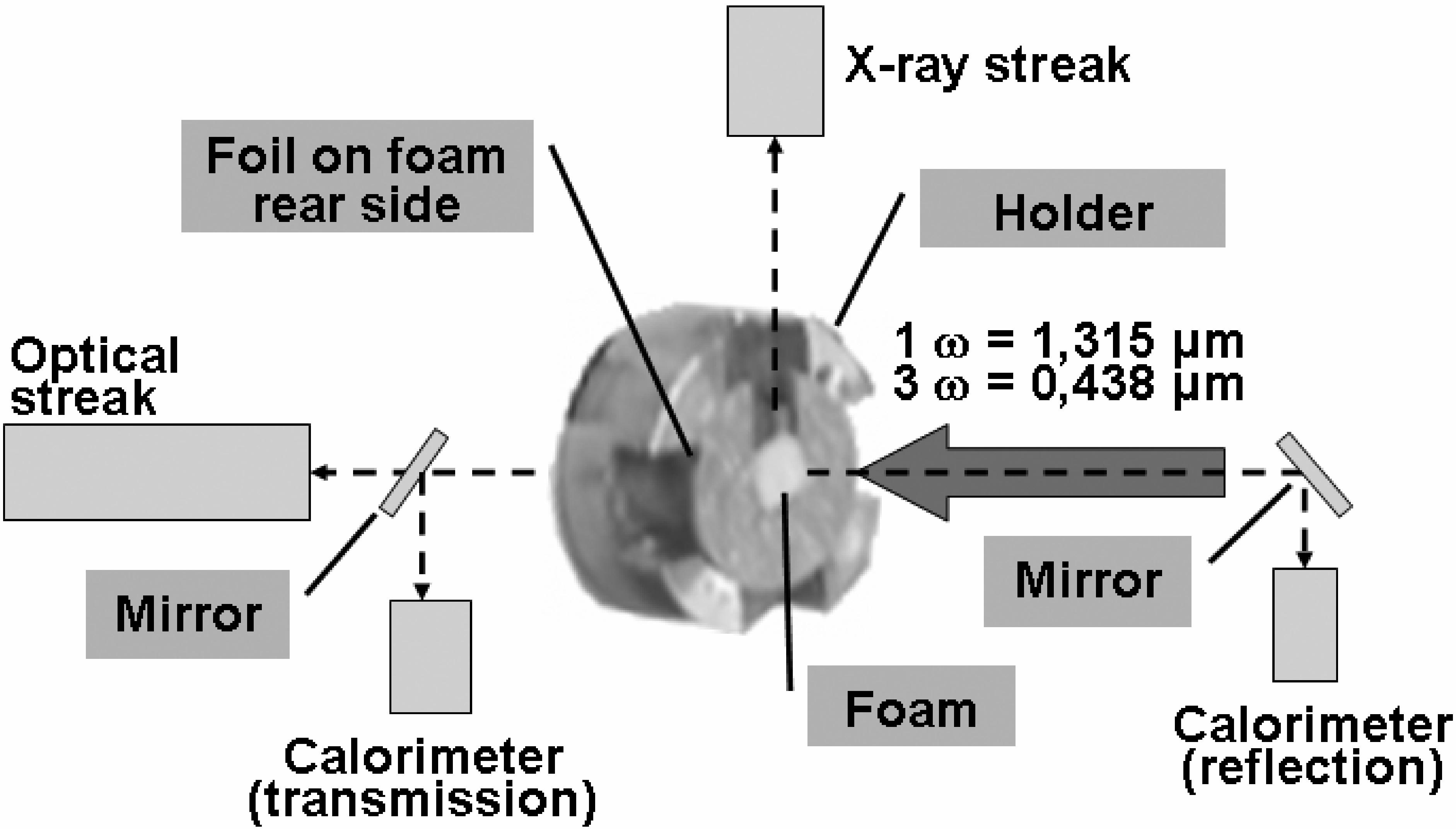
[1] Fill pressure and gas density estimations have been carried out using software created at LPI [I.V.Aleksandrova et al.J.Phys.D: Appl.Phys. **37**, p.1-16, 2004.]



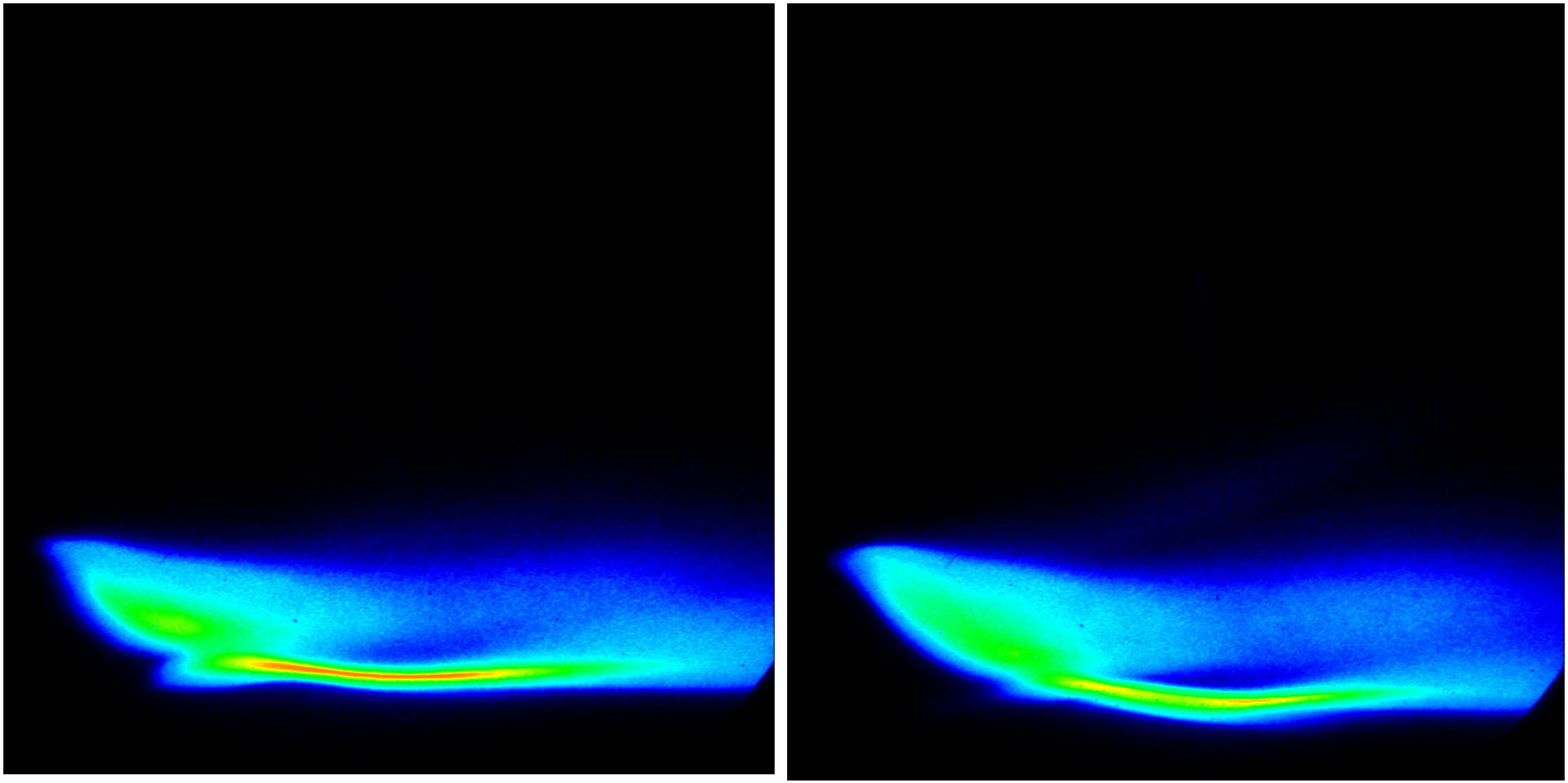
Application of low-density targets

- Energy transport are studied in low-density materials of various structure (open and closed cells, different cell sizes, etc.) with “Mishen” laser (Target) in TRINITI, Troitsk, Moscow region.
- Dependence of neutron yield on structure and density of deuterated target on laser “Neodim” in TsNIIMASh, in Moscow region and on pinch in Kurchatov Institute in Moscow.
- Experimental comparison of “thermal” method of heat-and-flow smoothing by volume-structured material on lasers PALS in Prague, LULI 2000, LIL in France and of “optical” method of a separate dynamical plasma phase plate on “Iskra-5” in VNIIEF in Sarov.
- Influence of dopants in low-density materials on energy transport on lasers PALS in Prague and “Kanal” in LPI in Moscow.
- The soft X-ray transmission imaging based on laser illuminated x-ray source in conjunction with parallel beam selection by x-ray mirrors verified the aerogel has <1% density variations in the interaction volume (talk of Igor Artyukov on MW TA 2007).

Diagnostic scheme of PALS

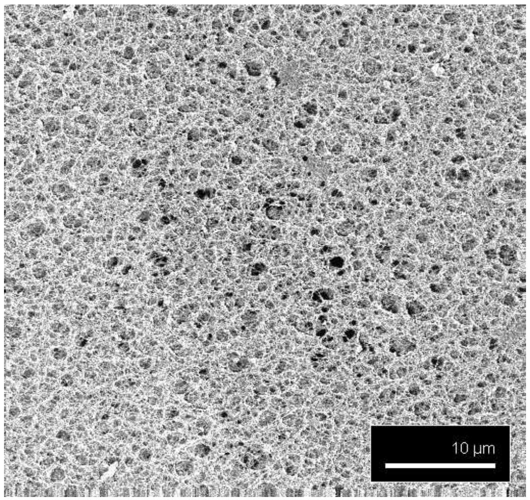


With stable laser performance and well characterized 3-D networks similar data are reliably reproduced due to uniform target structure



Shots #28233 and #28236 EL=165 J, TAC density 4.5 mg/cc, x-ray streak camera, time on the horizontal axis flows from the left to the right. The whole frame duration is 2 ns, laser light from above, the vertical spatial range is 2 mm. PALS iodine laser 3ω shots are reported from here on.

Underdense polymer targets: structuring and cluster doping for laser light absorption.

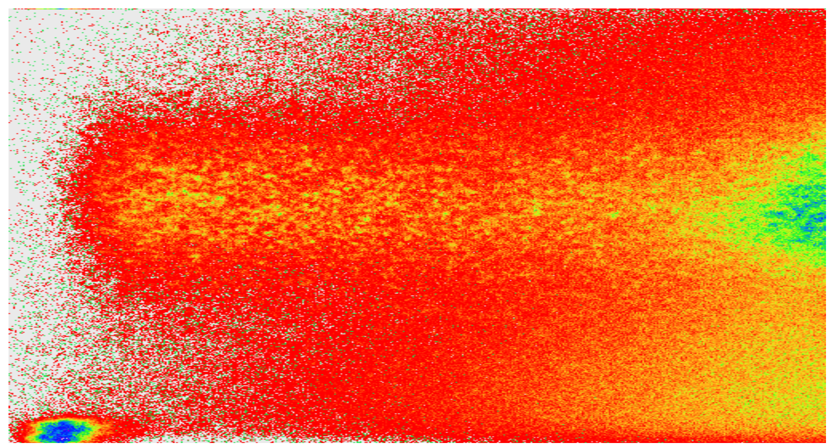


TAC

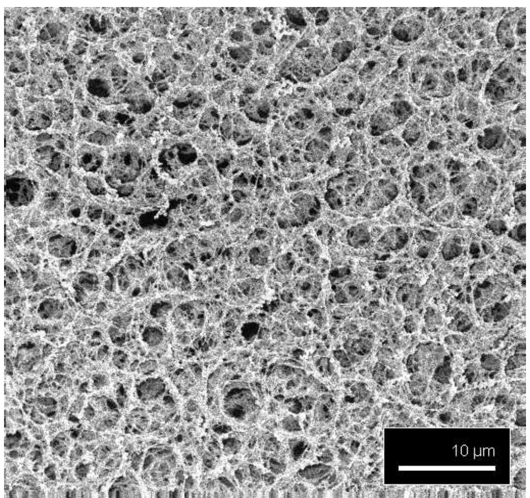
4.5 mg/cc,

X-ray streak Image of foam ⊥ laser beam

→ time period is 5.8 ns



Optical streak from the rear side of Al behind foam



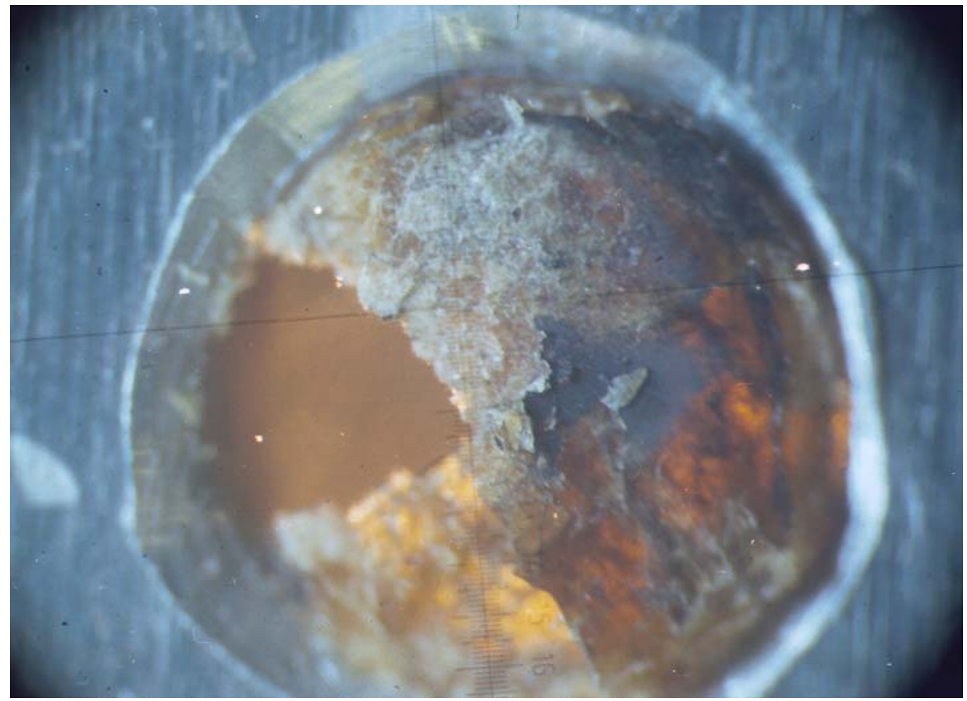
TAC+Cu

9.1 mg/cc,

Clusters in undercritical 3-D networks change energy transport in microheterogeneous plasma

Thin beryllium hydride film transformation to nanocrystalline beryllium film by interaction with short laser pulse.

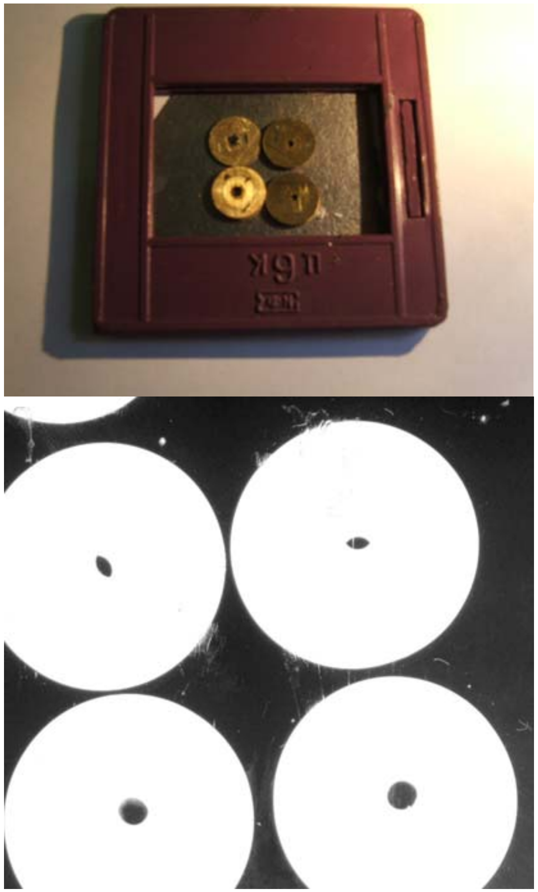
At ps-laser experiments of interactions with BeD_2 targets we accidentally found that BeD_2 can transform to Be-film with 3 μm thickness and nanocrystalline structure.
Now we try to produce Be-film and BeD_2+Be films with 0.5-1 μm thickness using various lasers.



BeD_2 targets after shot. Crater after intensive pulse. 3 μm Be-film appeared after laser irradiation of 10^{11} W/cm^2

Belyaev V.S., et al. Composition, Density and Structure Dependent Neutron Yields from Deuterated Targets in High-Intensity Laser Shot. // Journal de Physique IV (France), June 2006, Vol. 133, pp. 507-509.

Thin (<1 micron) film ($Be+BeH_2$) – x-ray filter for EUV multilayers (Mo/Si) mirrors (13.5 nm), EUV-streak and pin hole camera



←Photography of x-ray filters in optic and in 2 keV x-ray

↑ Photography of pin hole camera with thin (0.5 micron) ($Be+BeH_2$) x-ray filters

Yu.A.Merkuliev et al. Report on 29 ECLIM, 11-16 June 2006, Madrid, Spain.

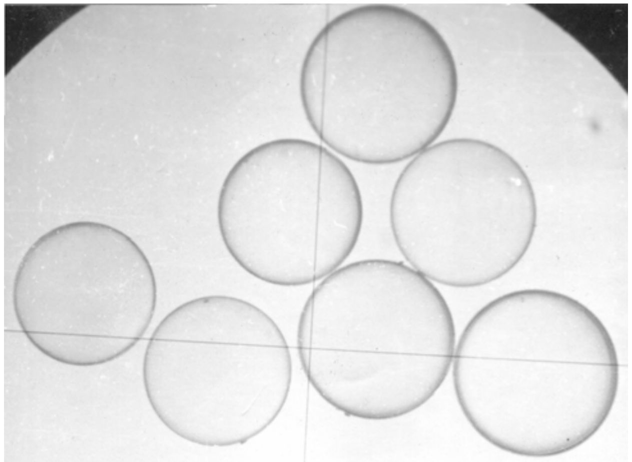
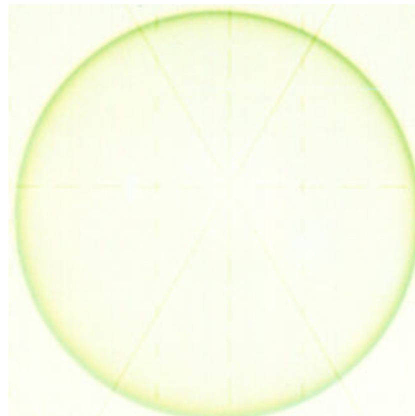
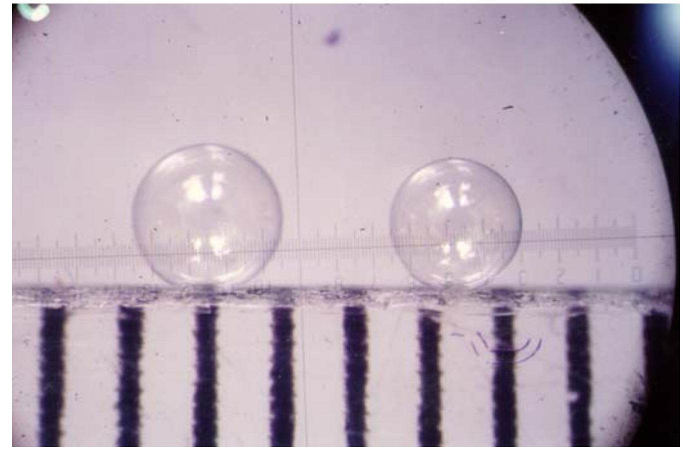
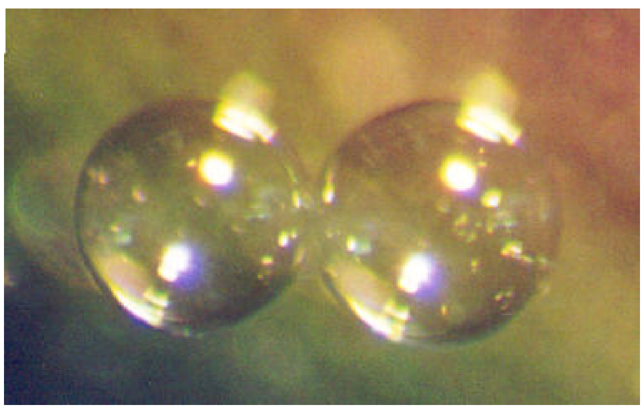
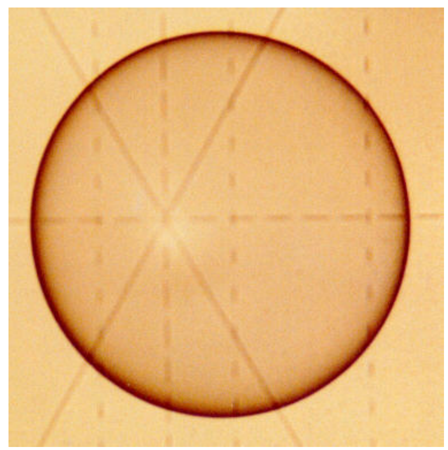
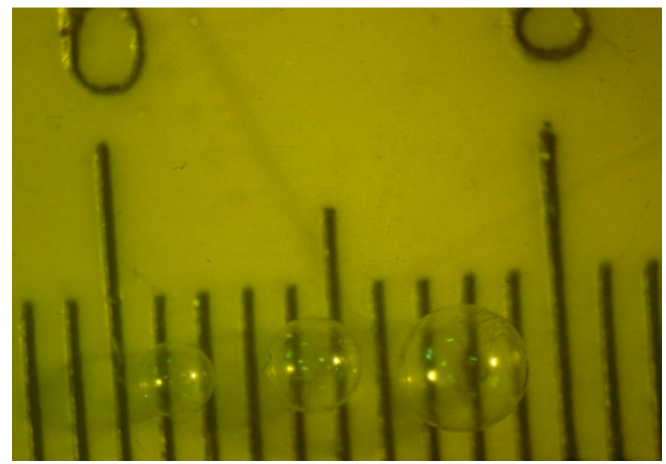
The results obtained in the Collaboration of Moscow Institute in 6 directions over the past 5 years are:

- **Large polymer and glass shells fabrication methods. Spherical shell-targets' technology and development including those of beryllium deuteride and amine-borane ND_3BD_3. (Yu.E. Markushkin poster)**
- **Working out methods and instruments for target characterization. Measurements of complex multi-component assemblies including monitoring of cryotargets, liners and target units for Z-pinch.**
- **Flat and spherical targets with low-density layers with/without high-Z nanoparticles' admixture to be used at various lasers or in Z-pinch liners.**
- **Hydrogen isotopes cryogenic-layer amorphization or thermal and durable layers study (talk of E.Koresheva)**
- **Development of free-standing cryotarget transport and delivery to the interaction chamber focus.**
- **Applications of target technologies for scientific devices components (super-thin Be-BeH_2 filters for soft x-rays' registration, special targets for ion accelerators and so on).**

Conclusion.

1. New large fusion targets from deuteride-tritide of light elements allow to organize the experiments with high gain by energy (cryo) or with surragate of cryogenic target.
2. Relatively cheap target from deuteride-tritide of light elements with the following isotope exchange can be used in experimental installations where target-driver (Z-pinches, heavy ions accelerators etc.) optimization is needed.
3. The experience of TTL (from Lebedev Physical Institute) participating in experiments with 10 different drivers is outlined. Cooperation with collectives of 7 facilities in our country and of 6 ones in 5 countries abroad in the past 5 years allowed us to participate in various experiments (ICF, EOS, etc.) .
4. TTL proposes to use our technologies of ($Be+BeH_2$) composite for EUV (13,5 nm) optics and plasma diagnostic.

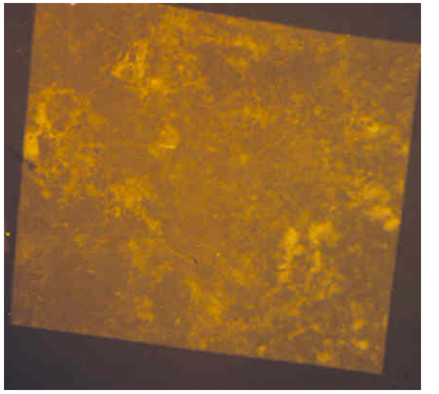
The targets for testing and experiments for scientific centers in UK, USA, France, China

Our targets were delivered for test or for shots to RAL UK, to LLNL USA, to Centre in Limey France and to Institute of Nuclear Physics and Chemistry in China

Targets from deuteride polyethylene with full density

Neutron yield 5×10^7 was at 10J, 1ps, 10^{18} W/cm^2 on laser "Neodim" in Russia on thick target from deuteride polyethylene plate with thickness 350 μm.



Photography of thick (350 μm) $(CD_2)_n$ layers

Craters in targets after shots. Left – laser incident, right – rear side.

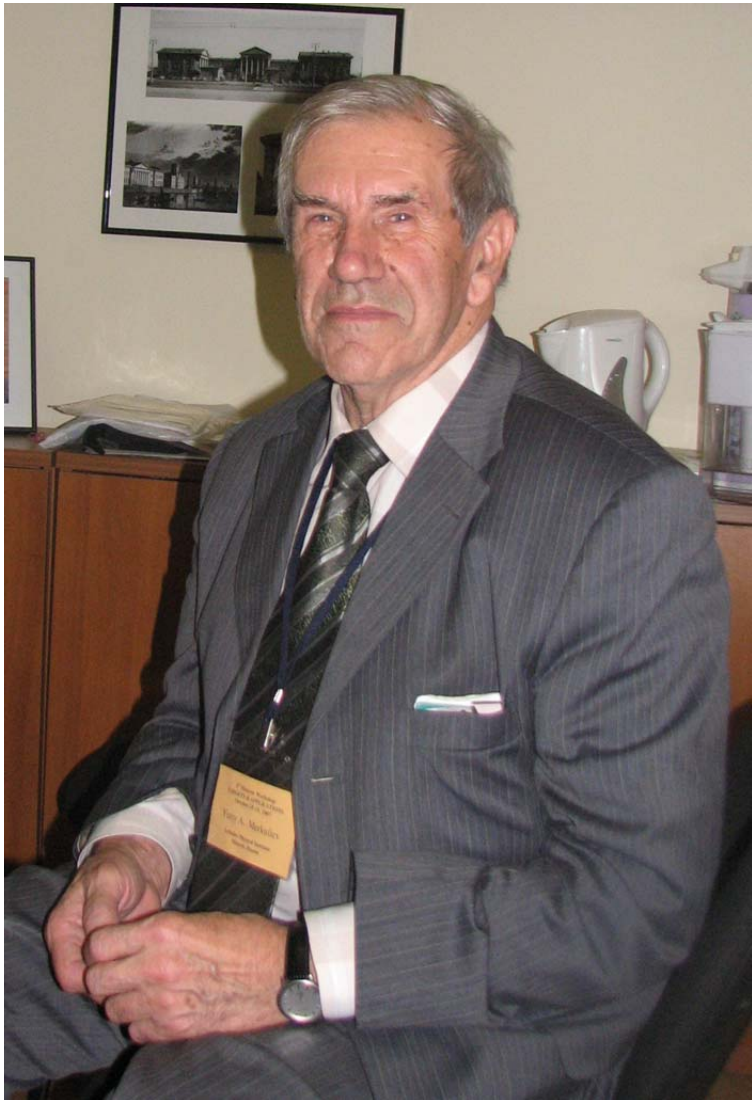
Crater in BeD2 targets after ps-laser shots.

Belyaev V.S., et al. Composition, Density and Structure Dependent Neutron Yields from Deuterated Targets in High-Intensity Laser Shot. // Journal de Physique IV (France), June 2006, Vol. 133, pp. 507-509.

Conclusion

Basic obstacles on way to high gain of targets

- RT instability and rising of ignition volume – targets symmetry and external fast ignition
- Turbulent mixture on boundary of shell wall and DT-layer – shell wall from materials with DT .
- Small efficiency of laser targets – using of foams for outer layers (also method of irradiation symmetry).
- Technologic difficulties of DT-layer formation in shell-target with outer foam layer – using Be-foams with high heat conductivity.



Yu.A. Merkul’ev