Target aspects in plasma experiments with laser and heavy ion beams

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Outline

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

- Thermonuclear Target Laboratory of LPI produces various targets. We also produce the equipment for target fabrication.
- TTL is the leader of target research in Russia and is responsible for “target factory” in “Iskra-6” program. We work in cooperation with different Institutes.
- We take part in large international projects (Iskra-6, HED&HOP (EC, GSI, Germany), HiPER (EC, UK), Petal (EC, France))
- Russian targets specialists take part in IFSA, ECLIM international conferences and IEAE meetings.
- Equipment and software developed in LPI and our laser targets are used in 7 Russian Institutes and in 9 Scientific Centers in 7 countries. Rep-rate cryogenic target fabrication and delivery to laser focus in interaction chamber.
- Current grants
  1. Extreme ultraviolet generation (EUV) and EUV diagnostic of dense cool turbulent plasma (magnetic fields and plasma viscosity)
  2. Equation of state (EOS) and pressure increasing in multilayers targets
  3. Laser irradiation smoothing by different methods (thermal – in polymer aerogel, x-ray – low-density metal or metal with polymer, optical – dynamic plasma phase plate).
  4. Rep-rate cryogenic target fabrication and delivery to laser focus in interaction chamber.
- Remark: Projects of targets factory, many targets deliveries and equipment creation require financing and time (1-3 years).
Equipment for the scientific centers in foreign countries in the years 1998-2003

The installations produced by LPI for glass and plastic shell target

High-temperature droplet generator for concentrated (60%) silicate solution.
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°C
FILLING SHELL PRESSURE
– 35 MPa
COMPUTER CONTROLLED
FILLING PROCEDURE

Second step:
thermocompression

FILLING CHAMBER P≤200MPa, T=350-400°C
HIGH ACCURACY
COMPRESSOR ∆P~0.1-0.2%

The system was created in LPI for VNIIEF in 2005.
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 wavelet analysis of 100 – 200 images for single or double-layer shell.

A.I.Nikitenko MP15 Report on Target Fabrication Meeting 1-5 October, 2006, San Diego, CA, USA

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)

Time of cryogenic layer formation (thickness <100 μm): t<15 sec
Furnaces for polystyrene microshells production

Drop tower furnace

Ballistic furnace
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.

\[
\chi = \frac{S}{4\pi R^2}, \quad \tau, \text{ sec} \quad q, \text{ K/sec}
\]

<table>
<thead>
<tr>
<th>$\chi$</th>
<th>$\tau$, sec</th>
<th>$q$, K/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.035</td>
<td>1.57</td>
<td>7.9</td>
</tr>
</tbody>
</table>

TARGET PARAMETERS
- Polystyrene shell: $\varnothing$ = 1500 mcm
- Shell thickness: 20 mcm
- Outer coating: 200 Å Pt/Pd
- Fill pressure (300 K): ~270 atm
- Gas density (300 K): ~38 mg/cm$^3$
- 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

E.R. Koresheva et al. Report on Target Fabrication Meeting 1-5 October, 2006, San Diego, USA

Cryogenic layer formed using the combined FST-layering

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

Parameters of laser radiation | Target parameters [1]
--- | ---
**Input Energy** - 300 kJ | 1. Mass of DT 0.1 mg
| Wave length - 0.351 mcm | 2. $\Delta R_{DT}$ 15 mcm
| Pulse duration - 8.5 nsec | 3. $R_0$ 1.46 mm
| 4. $\Delta R_{CH}$ 20 mcm | 5. $\rho$ (DT-vapor) $5\times10^{-4}$ g/cm$^3$
| 6. $T$ (DT-layer) ~19.6 K | 7. Fill pressure (300K) 42 atm

**Input Energy** - 500 kJ | 1. Mass of DT 0.171 mg
| Wave length - 0.351 mcm | 2. $\Delta R_{DT}$ 23 mcm
| Pulse duration - 8.5 nsec | 3. $R_0$ 1.54 mm
| 4. $\Delta R_{CH}$ 33 mcm | 5. $\rho$ (DT-vapor) $5\times10^{-4}$ g/cm$^3$
| 6. $T$ (DT-layer) ~19.6 K | 7. Fill pressure (300K) 60 atm

## Properties of solid hydrides of light elements

<table>
<thead>
<tr>
<th>Material</th>
<th>LiBeD₃</th>
<th>LiBD₄</th>
<th>BeD₂</th>
<th>(CD₂)ₙ</th>
<th>ND₃BD₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>≈0.83</td>
<td>≈0.86</td>
<td>0.765</td>
<td>1.10</td>
<td>0.92</td>
</tr>
<tr>
<td>Number Σ(Zᵢ+1) to 4 (number D₂)</td>
<td>2.5</td>
<td>2.25</td>
<td>2.25</td>
<td>2.75</td>
<td>2.167</td>
</tr>
<tr>
<td>Module of elasticity, GPa</td>
<td>27.3</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melting point, °C</td>
<td></td>
<td></td>
<td>140</td>
<td>(134)</td>
<td>106</td>
</tr>
<tr>
<td>(Glassy temperature),</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boiling point, °C</td>
<td></td>
<td></td>
<td>(≈350)</td>
<td>(≈520)</td>
<td>(≈300)</td>
</tr>
<tr>
<td>(Temperature of momentary disintegration)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability for H₂, cm²/atm.s,</td>
<td>&lt;5 · 10⁻¹²</td>
<td>10⁻⁶</td>
<td>≈10⁻⁹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical transparency (&lt;0.1 mm)</td>
<td>semi</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Surface roughness, nm</td>
<td>&lt;10</td>
<td>&lt;60</td>
<td>&lt;30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure (crystal, amorphous)</td>
<td>crys.</td>
<td>crys.</td>
<td>amor.</td>
<td>am-cr</td>
<td>crys-am</td>
</tr>
</tbody>
</table>

GNIIChTEOS specialists have been producing ND₃BD₃ since December 2004.
Dr. Yu.E. Markushkin with assistants fulfilled isotope exchange in ammonia-borane. In 6 hours 8 at% of H₂ was substituted for D₂

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.


Now in Bochvar Institute.

First shells from NH$_3$BH$_3$, fabricated in TTL on 14.04.03.

Some are optical transparent

Solid materials with high concentration of hydrogen isotopes

Materials with high content of deuterium (for example LiD, BeD₂, LiBeD₃, LiBD₄ or ND₃BD₃) 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 NT₃BD₃ 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 BeD₂ or LiBeD₃ foams layers can be used as absorbers of laser radiation and for fast heat transfer onto shell-target [6].

2. S.A. Belkov et al. Quantum Electronics (Russian), 2002, V. 32, No 1, p. 27.
Deuterated polyethylene foams for ps-lasers and liners.

The targets for experimental demonstration of increased neutron yield when using the foam targets with cells 30-50 μm

Targets from (CD₂)ₙ foam with density from 10 mg/cc to 100 mg/cc had been produced

(CD₂)ₙ foams, density 20 mg/cm³ and 40 mg/cm³

Photography of (CD₂)ₙ foams for liners/

Targets of plastic aerogel TAC for experiments with undercritical plasma density

Density fluctuations <1% in the focal area Ø 300 μm.
←Scale – 1 μm

TAC 10 mg/cc 300 μm in the holder with a slit on the kopeik

Similar repeatable submicron structure
(in the range 50 down to 1 mg/cc, inter fiber distance 0.7-1.6 μm, diameter 30-50 nm, fiber density 0.2 g/cc)

←Doping with Cu or Cl (15% mass) in TAC 10 mg/cc, Cu particles 40 nm, concentration 5·10^{12} cm^{-3}, 3% nanoparticles agglomerated
Average pore size

Computer procedure of 3-D network analysis to measure the cell size and fiber diameter

TAC of 10 mg/cc done Jan 15, 2005, average fiber distance (pore size) $\approx 1.5 \, \mu m$

Initial SEM image, scale bar 2 $\mu m$

Scanned intensity line ready for cell and fiber mathematical restoration

Image processed: denoised, illumination and contrast equalized, intensity scanning done along the red lines
Layers with density gradient needed for laser experiments

1. Density gradient targets with decreasing density or increasing stepwise density layers were considered in experimental and theoretic papers on astrophysics modelling, equation-of-state (EOS) and shock wave dynamics research. Earlier we have done the multilayered targets with increasing density for pressure amplification and energy transport velocity change [1,2].

2. The EOS studies and astrophysical modeling in intense laser interaction experiments will be even more meaningful with targets of smooth density gradient.

3. We search for the method to prepare a single smoothly increasing low-density layer instead of steps of density in the target.

4. Laser targets require high (>10 g·cm⁻³/cm) density gradients of the spatial profile for EOS experiments. The first targets from silica aerogel and polymer foam (regular as aerogel) with density gradient are demonstrated, but these targets have less (<1 g·cm⁻³/cm) density gradient then it is required.


Targets for EOS experiments with the pressure amplification

Scheme of EOS target

First layer for pressure amplification (foams or plastic)

Second layer

Third layer

Thick Al (Cu or Au) layer and one step

Step from research material
First attempts to produce 2 and 3 low-density layers from TAC

Scheme of multilayers target

First TAC foam layer
Second TAC foam layer
Third TAC foam layer
Thin Al - foil

Laser

TRINITI result
Target

Photo of 3 TAC layers with density 2.5 mg/cc, 5 mg/cc and 10 mg/cc after cutting
Growth of gel from catalyst boundary

4:37 p.m. start
2\textsuperscript{nd} frame: gel is being formed on the surface of the catalyst (5 min)
3\textsuperscript{rd} frame: silica layer has become continuous (7 min)
4\textsuperscript{th} frame: \(-2\) mm of gel on the boundary between catalyst and TEOS solution (7 min)
5\textsuperscript{th} frame: white sediment in the solution of ammonium in water (20 min)
8\textsuperscript{th} frame: eroding and following dimness of the forming gel (93 min)
10\textsuperscript{th} frame: the top of the substance is still swaying (228 min)
Gradient density gel formation dynamics researched by 3D X-ray tomography images. Tetraethylorthosilicate (TEOS) – \((\text{C}_2\text{H}_5\text{O})_4\text{Si}\) solution in alcohol with catalysis (ammonium hydroxide - \(\text{NH}_4\text{OH} \ 20\% \) in water) on contact boundary used for high X-ray contrast images creation.
Usual view of silicagel growth on x-ray tomography. Horizontal level of cross section is 3.14 mm. (near boundary TEOS solution and ammonia + water)
The pictures show horizontal cross sections silica gel during gel growth (from left to right) on levels 2.33 mm, 4.07 mm and 8.06 mm. TEOS solution boundary levels for different samples change from 2.5 mm to 3.3 mm. This sample boundary level is 2.7 mm from the bottom, left cross section has gas bubbles under silica gel membrane. Lower cross section has darker color, then upper cross section and gel has higher SiO$_2$ concentration. Middle and right cross sections have identical color. Gel growth front is stable (flat).
Dependence of SiO$_2$ concentration via height

Dependences of count tomography (CT) numbers on (from) height of TEOS solution (tube) during gel growth at various time after TEOS solution is placed on catalyst for two start concentrations: left – 0.5 basic solution, right – 0.25 basic solution. SiO$_2$ concentration can be found from comparison on CT number in table with SiO$_2$ concentration. Water diffusion into upper (5-7 mm height) gel layers (mixture of alcohol with water) increases CT number after 25 min observation (see table).
Target constructions with low-density layers from polymer foams and metal foams

Cylindrical targets for laser compression: left – instability research; center – heavy ions research; right – U-critical lever achievement at compression for HICF.

SEM images: top – polymer aerogel with density 1 mg/cc; bottom – metal low-density layer with nanoparticles of density 50 mg/cc.

X-ray image of glass shell with outer low-density metal layer, LPI, Russia.

Double shell with low-density aerogel, GA, USA.
Metal foams

Cu

scale – 10 μm

Au?? scale – 10 μm

Sn?? scales – 20 and 10 μm
Thermonuclear Target Laboratory (TTL) was established in 1974. For about 30 years the laboratory has provided the targets and targets fabrication equipments for the 11 scientific centers of Russia, Great Britain, Germany, France, Italy, Czech Rep., USA, India and China.

«Target Factory» created at TTL is an integrated facility including subsystems for microshells fabrication, surface coating, target quality characterization, fuel filling, fuel layering and target injection.

Available product:
- Hollow microshells from glass, polystyrene, Cu, etc.
- Mass glass and polymer hollow microspheres production
- Advanced materials to increase energy efficiency BeD₂, ND₃BD₃ and D↔T exchange in ready shell-targets
- Micro-heterogeneous and foam targets
- EOS experiments and astrophysics modeling targets for current research
- Surface coating
- Double-shell targets
- D₂ and DT-fuel filling
- Fuel layering
- Target quality characterization: interferometry, X-ray microscopy, micro-tomography

Prof. Yuriy Merkuliev, head of TTL since 1974
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 $\mu$m thickness and nanocrystalline structure. Now we try to produce Be-film and BeD$_2$+Be films with 0.5-1 $\mu$m thickness using various lasers.

Thin (<1 micron) film (Be+BeH₂) – x-ray filter for EUV multilayers (Mo/Si) mirrors (13.5 nm), EUV-streak and pin hole camera

EUV generation in laser targets and first experiments with EUV diagnostics of plasma from laser-target interaction.

**EUV Diagnostic scheme of KANAL - laser**

- Laser targets for EUV registration of plasma cooling after laser shot
- Pin-hole EUV camera with thin (1,5 μm) Be+BeD₂ composite optical filter

**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification, $M$</td>
<td>24.26</td>
</tr>
<tr>
<td>Focal length, $F$</td>
<td>26.90 mm</td>
</tr>
<tr>
<td>Numerical aperture, $N_a$</td>
<td>0.19</td>
</tr>
<tr>
<td>Large mirror curvature radius, $R_1$</td>
<td>100 mm</td>
</tr>
<tr>
<td>Large mirror diameter, $D_1$</td>
<td>50 mm</td>
</tr>
<tr>
<td>Small mirror curvature radius, $R_2$</td>
<td>35 mm</td>
</tr>
<tr>
<td>Small mirror diameter, $D_2$</td>
<td>10.6 mm</td>
</tr>
<tr>
<td>Hole diameter, $D_h$</td>
<td>10.6 mm</td>
</tr>
<tr>
<td>Mirror separation for exactly coincident curvature centers, $\Delta R$</td>
<td>65 mm</td>
</tr>
<tr>
<td>Spacing between object and curvature center, $S_o$</td>
<td>28.19 mm</td>
</tr>
<tr>
<td>Spacing between image and curvature center, $S_i$</td>
<td>599.474 mm</td>
</tr>
</tbody>
</table>

**Legend:**

- F₁ – filter from BeD₂+Be
- P-H – pin-holes camera
- D2 – D5 detectors with x-ray films
- EUV multilayered mirror
- Objective from multilayered mirrors
- Vacuum camber for laser interaction with target
Shots comparison from PALS and LIL

The processes important for the energy balance were studied in these experiments:

1- laser light diffusion through microturbulent plasma and aerogel in the vicinity of the critical plasma density and light transmittance via target density and thickness;
2 – part of laser pulse energy transferred into SRS, SBS, harmonics;
3 – heating of Al (Cu)-foil (shell) by passed and by converted radiation, which result in the material flux meeting and slowing down the main heat-and-material wave in the low-density matter;
4 - special computer data processing of the images from large dynamic range (12-14 bit in black-and-white) streak cameras in X-rays and in the visible range was applied. It proved the weak preheat of the metal substrate long before the main shock and heat arrive to it through aerogel.

Results from third harmonic radiation lasers of PALS and from second harmonic of LIL:

laser on light transmission through microheterogeneous plasma match each other.
Weak signals from x-ray and optical streak-cameras are recorded.

Results from basic frequency of PALS and of MISHEN on previous heating of Al-foils through aerogel/plasma are consistent to each other.

Results from PALS and from LIL on plasma formation velocity in two-layers (aerogel + metal foil) targets coincide.

Plasma jet flight through aerogel with copper nanoparticles is slower than without additives.
LIL irradiation and diagnostic scheme

The LIL experiment

- Side-on time resolved X ray 1 D imaging
- With or without Cu foil

- Pinhole camera
- SRS and SBS backscattering
- Time resolved hard X-ray 2D imaging
- Foam 7-10 mg/cc L=500μm-1 mm doped with Cl

− visualization of the ionization front
− measurement of the foam ionization energy budget
− foam effect on laser backscattering
− validation of the foam smoothing effect

- LASER
  - 10 kJ of 351 nm light
  - 2.7 ns square pulse
  - minimum SSD level (< 1 Å)
  - 1 mm spot size
  - 3×10^{14} W/cm² on target

- Transmitted beam diagnostic
  - absolute power
  - angular distribution

- ~ 0.8 m
- 6°
- f =8 m
- cible

[IFSA 2007]
Laser radiation transmission through undercritical aerogel.

Foam parameters: TAC, 6.7 mg/cc, 0.95 mm

Laser pulse

Transmission through homogeneous plasma

Light transmission through inhomogeneous plasma and aerogel

Stimulated Brillouin scattering

Stimulated Raman scattering

Normalized signals from laser, transmission of laser radiation, stimulated Brillouin scattering, stimulated Raman scattering. (LIL 2007 experiment)
Diagnostic system of PALS
PALS x-ray streak-image in comparison with LIL data

Similar fluxes give close ionization front velocities
PALS irradiation and diagnostic scheme
Optical signal intensity via time on the rear side of the aerogel target (no foil) - PALS

Intensity, arbitrary units

Without target

Density 9 mg/cc (1/2 \( \rho_{cr} \))

Light transmission through homogeneous plasma

Layer thickness:
- 100 \( \mu \)m
- 200 \( \mu \)m
- 400 \( \mu \)m

Time, ns

Light transmission through inhomogeneous plasma
Continued: the same density, varied thickness of target

Transmission dependence on aerogel density

Shot-to-shot reproducibility

Light transmission through homogeneous plasma

Light transmission through inhomogeneous plasma

TAC, 9 mg/cm³ – 400 μm (245) $1/4 n_{cr}$

TAC, 4.5 mg/cm³ – 400 μm (251) $1/4 n_{cr}$

no target (255)

9 mg/cc – 100 μm (263 и 264).

(255) no target
Weak signals of Al-foil emittance prior main heat arrival

28204, 4.5 mg/cc, 400 μm
28232, 9.1 mg/cc, 400 μm
28231, 9.1 (TAC&Cu) mg/cc, 400 μm
Bright and weak signals from X-ray streak-camera

28232, TAC 9.1 mg/cc $1/4 \text{ ncr}$, 400 μm

28231, 9.1 mg/cc, 0.9 TAC +0.1Cu, 400 μm
Basic interaction results.

- Similar plastic aerogels (regular open-cell foams, 3-D networks) of TMPTA (Nazarov) & TAC (Borisenko) used to smooth the radiation nonuniformities from different powerful lasers perform other physical processes in microheterogeneous plasma as well, which are essential for the energy transfer models.
- Large dynamic range of registration characterized both optical and X-ray streak-camera images. The analysis of already published experiments on PALS and LIL is done addressing signals only several-fold higher than the noise.
- Their processing shows the weak heating of metal-foil on the rear of the aerogel (but not heating of polymer with close cells structure) to appear long before the main heat arrives by thermal conductivity and hydrodynamic waves. (on third harmonic its level is about 2-7% from full laser energy, on main frequency <0.3-0.8% < noise level)
- Part of the energy in the beginning of the laser pulse is transferred through the turbulent plasma and/or is transformed into SRS, SBS passing through optically transparent 3-D polymer network.
- Measured light transmission through the microturbulent plasma and the non-linear optical effects help to explain how the solid foil is heated through the aerogel.
- Results on basic frequency of laser MISHEN and PALS indicate that main heat of plasma in polymer aerogel from laser energy absorption localizes in small volume and quickly (70-120 ps) cools at moving in polymer network. The energy transport from target surface realized then in hydrodynamic wave is low.
Acknowledgements


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References FS&T 2008


