Development of a full-scaled scenario for repeatable IFE target fabrication and injection based on the FST technologies.

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IAEA RCM, Vienna, Nov 4-7, 2003

IFE target factory for the fueling of a burn area of IFE power plant with a rate of 1-10 Hz

Main issues associated with the task of target factory creation

- Elaboration of the efficient methods of target production
- Design, engineering and construction of the corresponding layering module
- Technology options for target/ injector interface
- Rapid control of target quality
- Development of the technology to protect target parameters from destruction during delivery

In this report we will consider the possibilities to solve the enumerated issues using the free-standing target (FST) technologies developed at the Lebedev Physical Institute (LPI)

In our institute the FST facility has been created that allows to fill, layer, characterize and inject 1 mm targets into a test optical chamber with the rep-rate up to 0.1 Hz

FST facility was upgraded over the period of 2000-2003

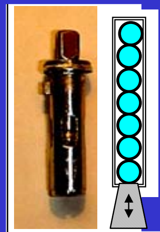
- Facility was completed with two sub-systems for shells and cryogenic targets characterization using tomography data processing methods. The subsystems work both with pre-mounted and free-standing targets.

- Layering module was modified for operation with the shells of ∅ 1.2-to-1.8 mm.

- Test chamber was completed with new components, namely:

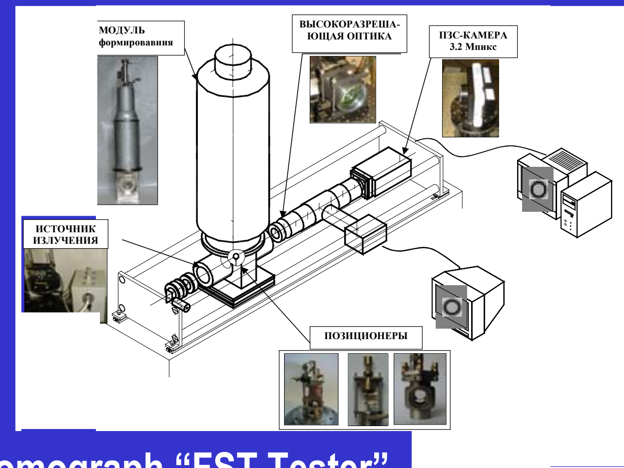
- Target positioning devices which allow to obtain free-standing target scanning in 100 projections (and more) with a given angle step.
- The R&B cell which is currently used for (a) target multi-views observations (number of projections is open), and (b) target science and technology researches.

The upgraded FST facility



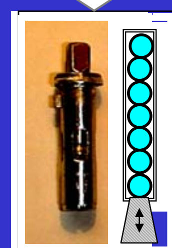
Shell container
(5-to-25 empty shells)

Fill system



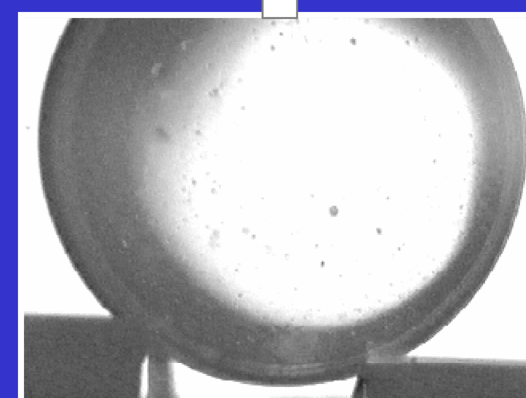
Tomograph “FST Tester”

Tomograph “Shell Tester”

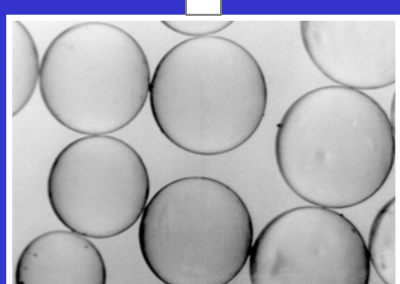


Shell container
5-to-25
gas-filled shells

Layering module



Target multi-view study (100 views)
using the positioning device



Current status of cryogenic targets fabrication by the FST technologies

PARAMETER		STATUS LPI (demonstrated in [1-3])	IFE REQUIREMENTS [2,4-7]
O.D.		0.5÷1.8 μm	4÷6 μm
Fuel material		D_2+ dopant (0.3-to-16 %) (demo.: D_2+Ne;H_2+HD; H_2+D_2)	DT-fuel
Fuel thickness		10-to-100 μm	200-to-300 μm
Outer layers	**Metal reflective layer**	Pd, Pt/Pd or Au 100-200 Å	Pd, Au
	Cryogenic protective layer	Cryogenic solid layer on target outer surface	Cryogenic protective layer
Target production rate		0.1 Hz (max)	1÷10 Hz
Fill pressure		100-to-1000 atm	427 atm (for DT in 4mm target) 423 atm (for D_2 in 4mm target)

[1] E.R.Koresheva et al. Proceed.1st IFSA (Sept.11-19 1999, Bordeaux, France) in.: Inertial Fusion Science and Applications'99 (ELSEVIER) p.897, 2000; [2] I.V.Aleksandrova et al. Proceed.2nd IFSA (Sept.11-19 2001, Kyoto, Japan) in: Inertial Fusion Science and Application 2001 (ELSEVIER) p.762, 2002; I.E.Osipov et al. ibid p.810 [3] E.R.Koresheva et al. Fusion Sci.&Tech. **43** N3 p.290, 2003
[4] M.Monsler et al. Pt.3. Target fabrication and positioning. p.153 (Table 3.3.1) in: Energy from Inertial Fusion (IAEA eds), 1995;
[5] S.Eliezer et al. Nucl.Fusion **37** p.985, 1997. [6] Resume of the IAEA RCM of CRP on the Elements of IFE Power Plants. IAEA Headquarters in Vienna, Austria, 21-24 May 2001. [7] D.T.Goodin et al. Fus. Eng.Design **60** p.27, 2002

The IAEA Project #11536

Whether it is possible to apply the FST technologies developed at LPI as a basis of IFE target factory?

- **1st year activity (2000-2001):** Theory, simulation program and numerical experiments for modeling the FST for reactor-scaled targets production.

MAIN RESULT: **Theoretical research carried out during the 1st year has shown that the existing FST system can be used for the first experiments with IFE targets.**

- **2nd year activity (2002-2003):** Further development of the design of the existing layering module and equipment, focusing on the layering module (LM) and injector assembly.

*MAIN RESULT: We propose a c***onceptual design of a system for the LM and injector assembly. The system also serves for repeatable assembly of the unit-1 "cryogenic target & protective sabot & protective cover" and/or the unit-2 "cryogenic target & sabot ".**

- **3rd year activity (under way):** Development of a full-scaled scenario for repeatable IFE target fabrication and injection based on the FST technologies.

CURRENT RESULT: We propose to **create the IFE Target Factory prototype for demonstration of the repeatable IFE targets fabrication and injection using the FST technologies.**

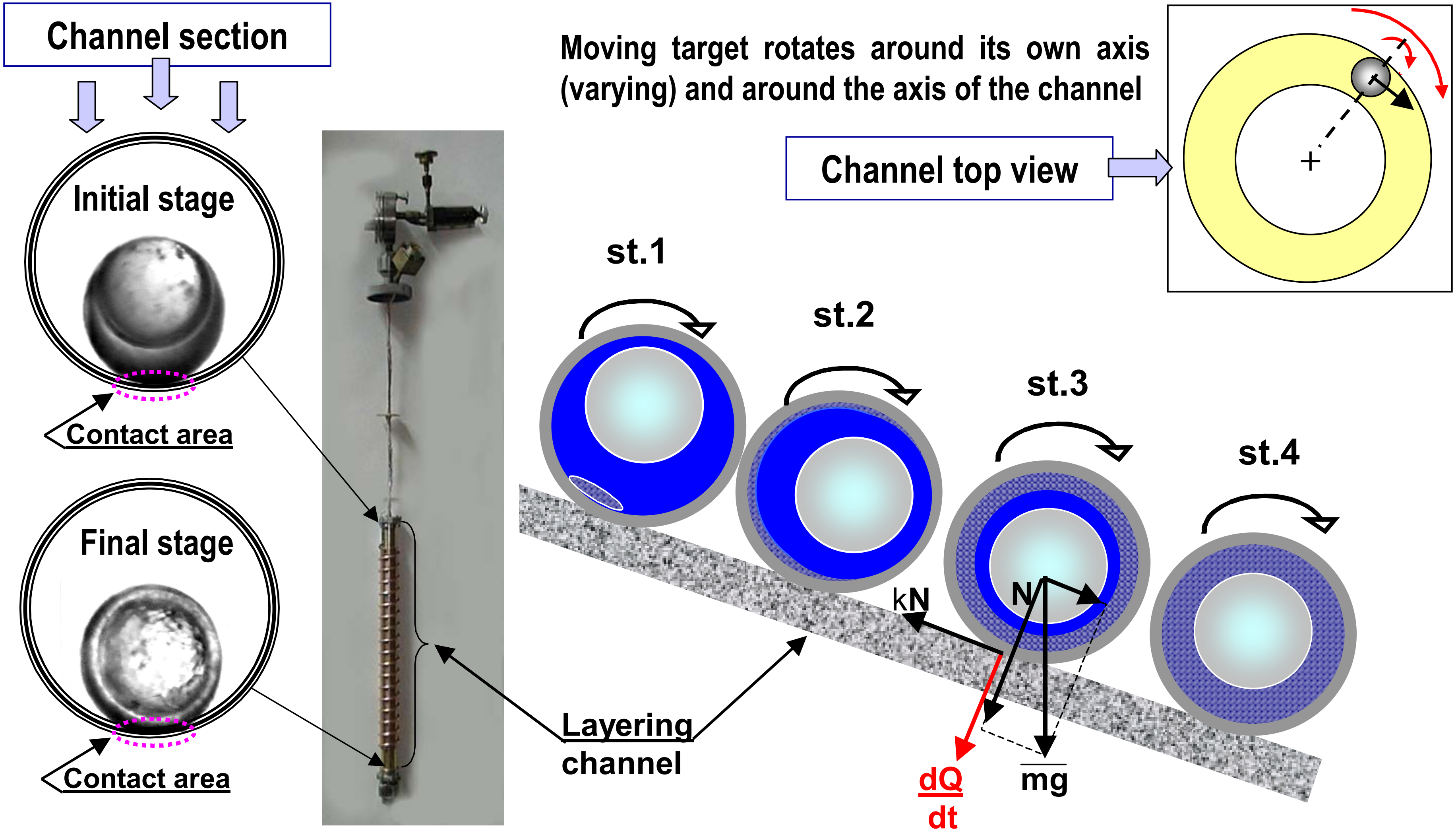
We like the FST-layering because it is rapid and repeatable

- **Rapid thick layering**
  Performed:
  2R $\leq$1.8 mm, W$\leq$100 μm, layering time <15 sec

- **Repetitive operation of the layering module**
  Performed: 0.1 Hz

The FST-layering is based on two principles:

1. Fuel freezing due to heat removal through the contact area between the shell and the channel wall.
2. Layer simmetrization due to target random rotation



FST: theoretical modeling for IFE targets

- FST theory worked with a typical target of 1 mm diameter with wall thickness up to 25 μm, fuel mass 0.03 mg

- In the contract #11536 we change over to large targets of about 4-to-6 mm diameters and wall thickness in the range of 45-500 μm with fuel mass > 2 mg

- We improved our simulation program and made numerical experiments for two type of classical high gain targets (CHGT):

  1. CHGT-1: CH shell ∅ 4 mm, ΔR=45 μm, W=200 μm (calculated for D2)

  2. CHGT-2: CH shell ∅ 5.5-6 mm, ΔR=300-500 μm, W=200-500 μm (calc.for D2)

Theoretical estimations have shown: existing layering module can be used for first experiments on IFE target formation with a configuration similar to CHGT-1

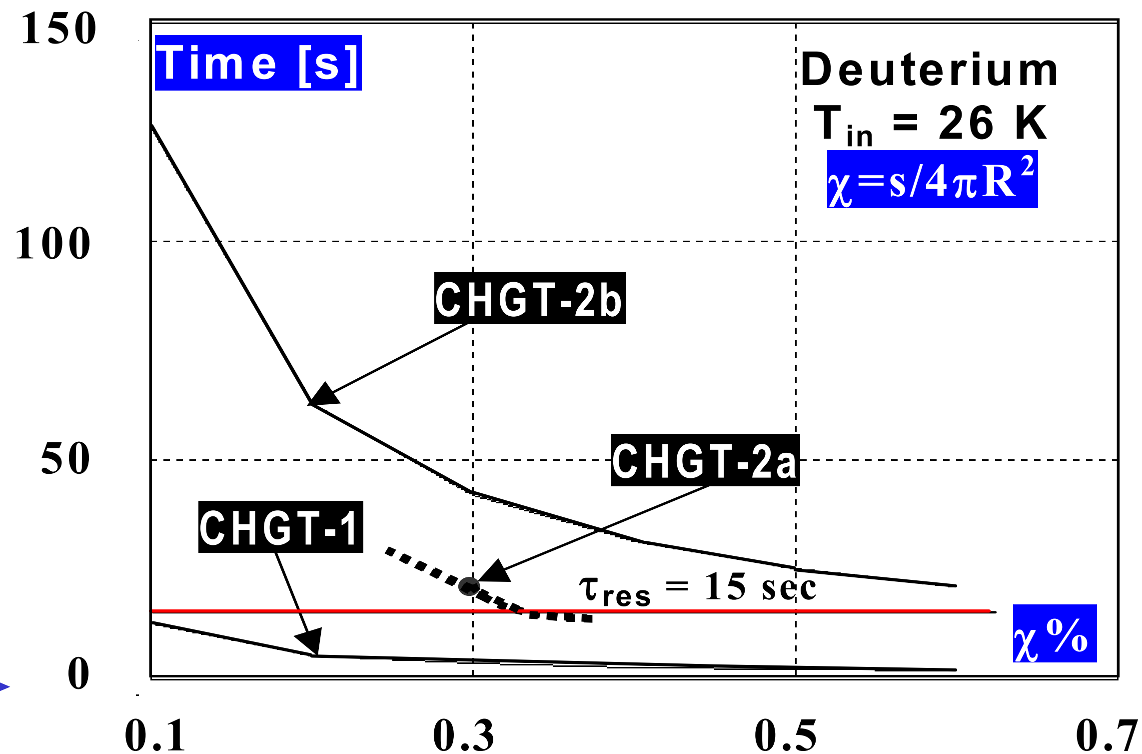
- Task

Determination of the layering time as the function of relative area of contact χ between the shell and the cold wall.

- Solution

Solution of the Stephen's task for moving interphase fuel boundaries (gas-liquid, liquid-solid) for non-linear boundary conditions on the outer surface of a shell (numerical solution).

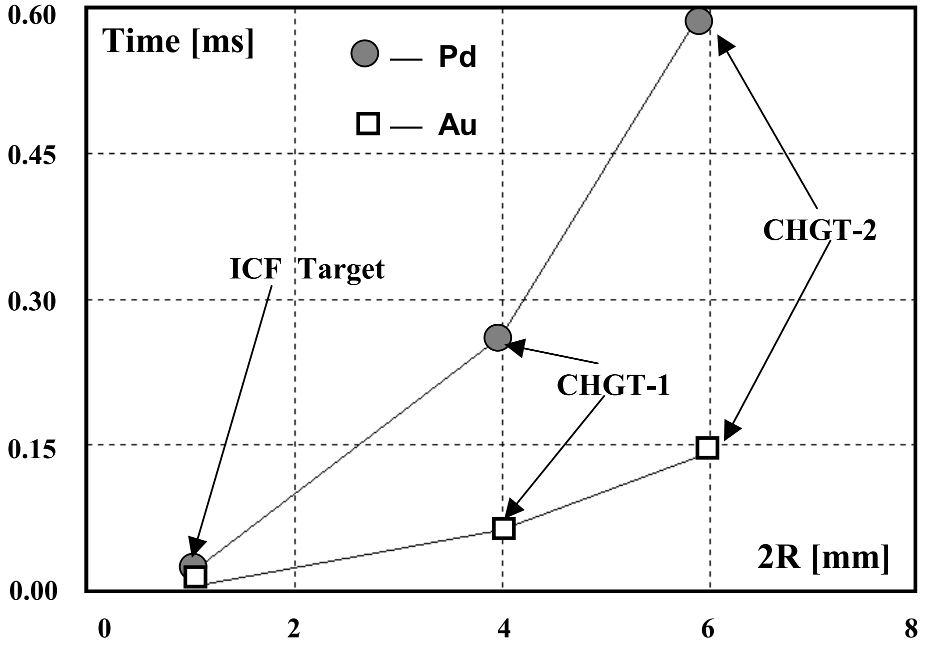
-Result



The layering time *vs.* the parameter χ

CHGT-1: CH shell ∅4 mm, ΔR= 45 µm, W= 200 µm
CHGT-2a: CH shell ∅5.5 mm, ΔR= 300 µm, W= 200 µm
CHGT-2b: CH shell ∅6 mm, ΔR= 500 µm, W= 500 µm

Outer metal coating dramatically influence on the contact area expansion



Preliminary calculations of the metal layer the cooling time for the palladium and gold

Results of the FST-layering inside CH shell with Pd coating.

Experimental conditions: modified layering module, shell ∅1.4 mm, Pd coating 150 Å, 51 μm solid H_2-layer

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ICF target: CH shell ∅ 1 mm, ΔR= 5 μm, W= 100 μm
CHGT-1: CH shell ∅ 4 mm, ΔR= 45 μm, W= 200 μm
CHGT-2: CH shell ∅ 5.5-6 mm, ΔR= 300-500 μm, W=200-500 μm

Estimated freezing time for CHGT-2

- no metal layer: τ_{freeze} = 66-to-127 sec

- outer metal layer: τ_{freeze} = 10- to-30 sec

Dynamical layer symmetrization by FST (1)

We have solved the shallow water equations for a rolling spherical target

RESUME: no layer symmetrization can be expected for steady-state rotation

❑ Problem formulation

3D equations for incompressible liquid (liquid velocity **V** << sound velocity) :

1.Navies-Stokes equation $\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\nabla)\mathbf{V} = -\frac{1}{\rho}\nabla P - g_{\otimes}\mathbf{e}_z + \nu\Delta\mathbf{V}$

2.Continuity equation $div\mathbf{V} = 0$

3.Hydrostatics equation $P = \rho \cdot \left(\frac{U_\vartheta^2 + U_\varphi^2}{R} - g_{\otimes} \cdot \cos\vartheta \right) \cdot (r - R + H)$

NOTATIONS

r, ϑ, φ are the spherical coordinates in the system T connected with the target,

$g_{\otimes}$ is the liquid acceleration,

R is the target radius,

H is the layer thickness

$\boldsymbol{U}$=-[**R**×**Ω**] ,

Ω is the vector of instantaneous angular velocity,

Θ and Φ are the spherical angles of the vector **Ω.**

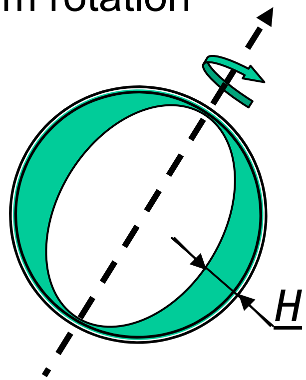
❑ Problem solution

Two cases are important to understand the mechanism of dynamical layer symmetrization by FST: steady state rotation and random rotation

1) <u>Steady- state rotation of the target</u> $(0 \leq \vartheta \leq \pi/4)$

In the case of steady- state rotation the layer thickness by rough estimation is: $H \approx const \cdot sin\vartheta$,

and no layer symmetrization can be expected



Dynamical layer symmetrization by FST (2)

RESUME:

Significant reduction of layer NU can be reached at target random rotation

- **Problem solution**

2) Effect of rotation axis wobble:

- the vector of instantaneous angular velocity $\Omega(t)$ is time- and space- dependent:
- the angles Θ and Φ are not correlated and change randomly near their mean values so that

$\Theta = \frac{\pi}{2} + \mu \cdot W_1(t)$ and $\Phi = \eta \cdot W_2(t)$, where $W_1(t)$ and $W_2(t)$ are the random processes in the range [-1, 1], and μ, η are the numerical coefficients ~ 1:

In the case of rotation axis wobble the layer nonuniformity along the shell can be estimated as

$$H^2 \cdot \left(R\Omega^2 \cdot \left(\cos^2 \vartheta + \frac{\mu^2}{3} \sin^2 \vartheta + \frac{\eta^2}{3} \right) - g \cos \vartheta \right) \approx const$$

ESTIMATIONS

A NU < 10% can be reached at

$$0{,}82 < gR/V^2 < 1{,}04$$

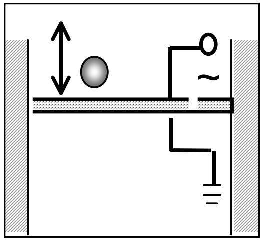
Theory:
V_{target} **~ 9.7 – 12.0 cm/s**

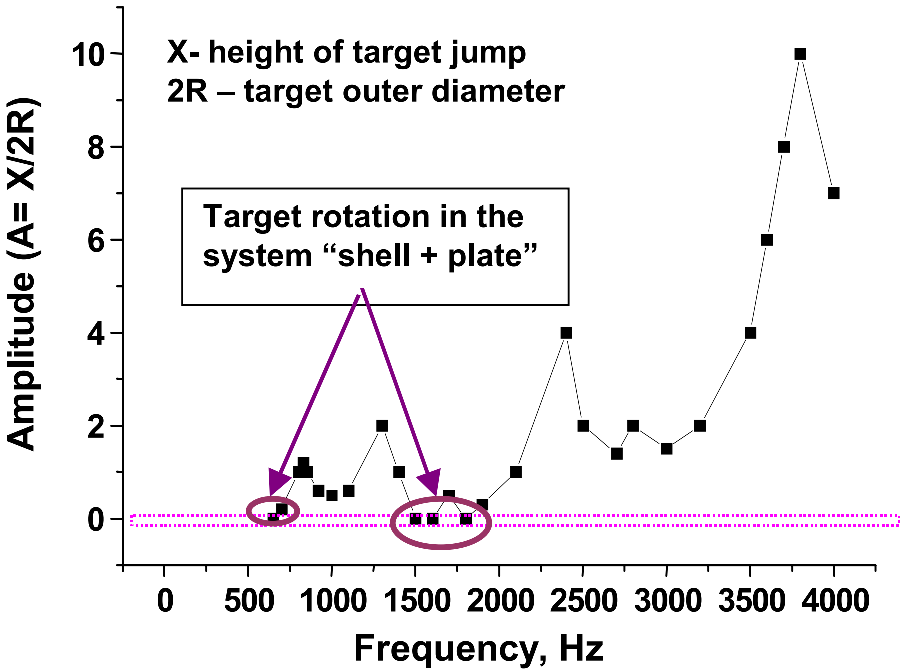
Experiment (spiral channel length l=1.5 m):
residence time 15 s, $< V_{target} > \approx$ **10 cm/s**

RESUME: **using the existed layering module we can reach the necessary conditions for layer simmetrization**

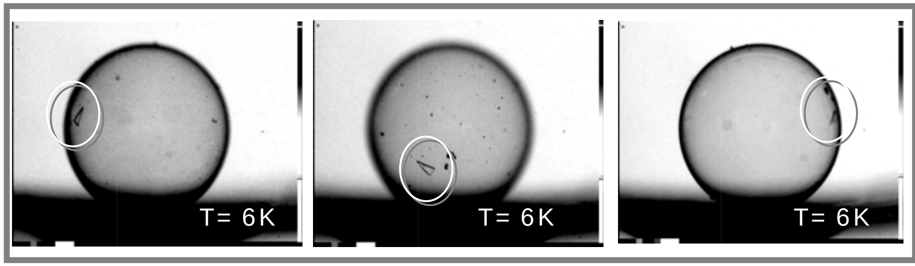
Optical test chamber is completed with the R&B cell, which has been used to prove theoretical results

- R&B cell operates using the principle of reverse piezo-effect
- Work temperatures of 4.2-30 K
- Permissible cooling rate of 0.1- 50 K/min

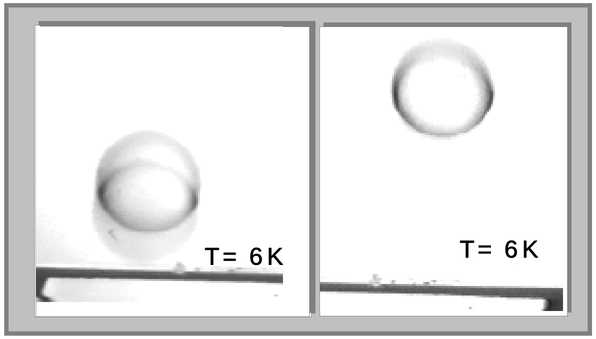




Results of the R&B cell testing

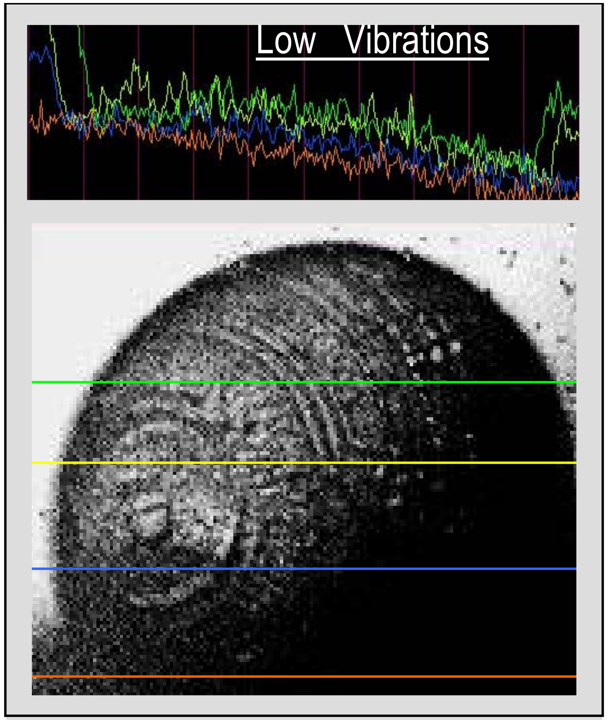


Rotating mode: H=600 Hz, U=75V



Bouncing - mode: H=3,7кHz, U=75V

Dynamical layer symmetrization by FST (3) Experimental results with the R&B cell



Modulated Layer Crystallization

- A feature of the FST is a random target rotation in the layering module. We have run a set of the test experiments using the R&B cell in support of this state.

- Experimental conditions:

— special regulations were set up to generate a steady- state rotation of the target

— a low background of vibration was superimposed to visualize the rotation axis

- Experimental results:

— a modulated layer crystallization appears along the rotation axis

— a uniform layer formation becomes impracticable

RESUME: The necessary condition of the FST layering procedure is a spatial delocalization of the target rotation axis.

Theoretical and experimental results are in close agreement

Rapid Simmetrization

Key parameters of the experiment:

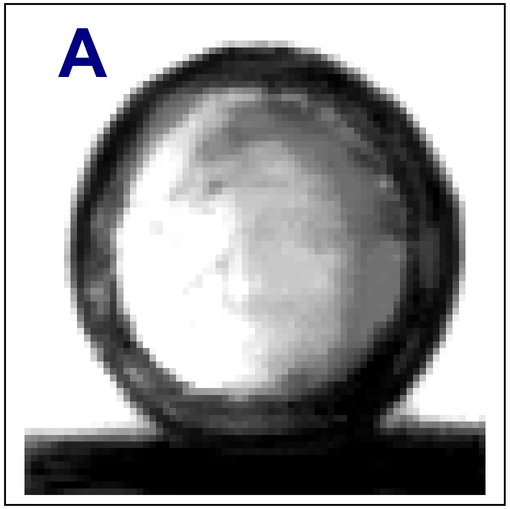
- Temperature of the target input into the channel T_{in},
- Channel geometry (length, shape)
- Temperature profile along the channel

Matter	Shell dia, μm	T_{IN}, K	W (μm)	$t_{residence}$, sec (exp)	τ_{freeze}, sec χ =0.003÷0.001 (calculated)	$NU_{initial}$ %	NU_{final} %
H_2*	983	21	88	8	1÷4	100	< 30
H_2*	985	15	88	6	0.3÷1.4	100	100
D_2**	980	26	30	12	2÷6	100	< 20

*/ cylindrical channel, **/ spiral channel

Results of the FST-layering optimization

OPTIMIZATION PARAMETER: TARGET TEMPERATURE INPUT TO CHANNEL T_{IN}



TARGET AFTER FST
T_{IN}=21 K

EXPERIMENTAL CONDITIONS:

Shells from polystyrene

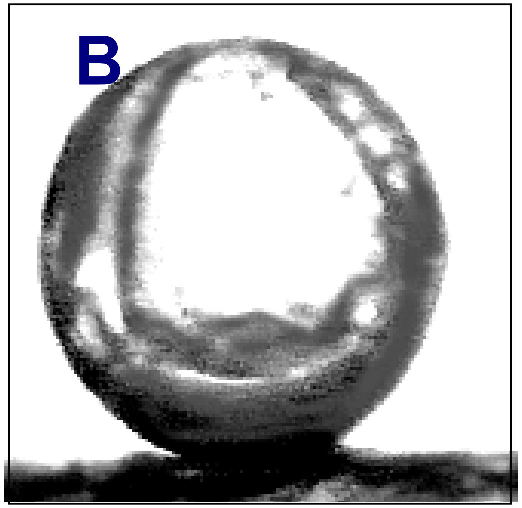
∅ ~ 986 μm and 989 μm,

Solid layer ~ 90 μm H_2

Cylindrical channel ∅3mm

Pressure of heat-exchanged

He in the channel



TARGET AFTER FST
T_{IN}=15 K

Results of the theoretical calculations and of the experiment are in a good agreement: time of the liquid phase existence in case B is insufficient for symmetrization.

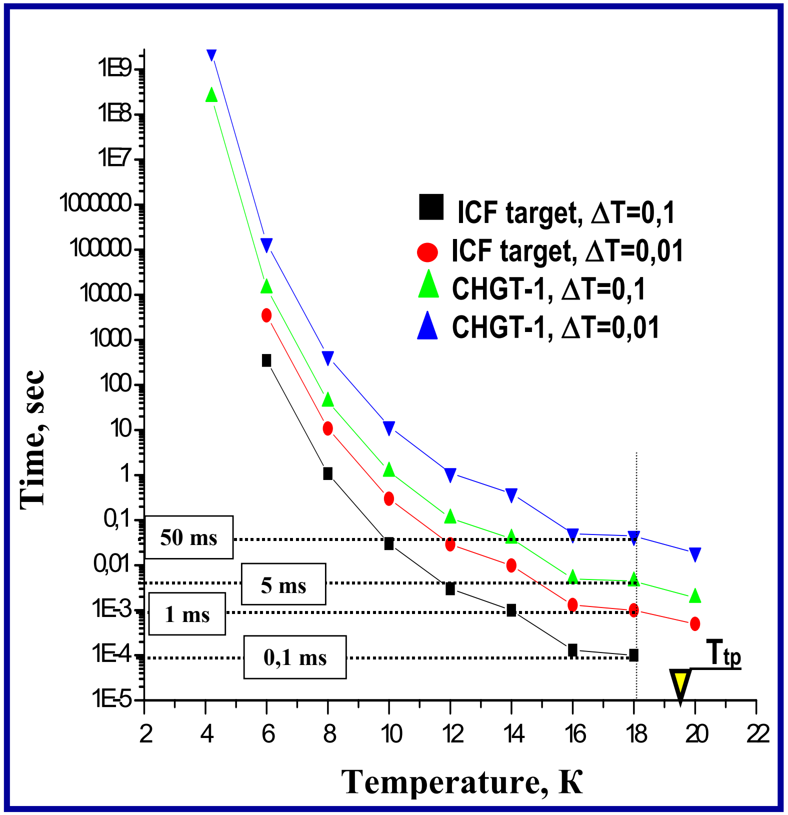
Target delivery. Fuel layer non-uniformity arising due to asymmetry of the heat flow

Process of solid H_2 migration to the coldest area of the target inner surface (T=12 K, ΔT= 0.007 K)

Time of the fuel layer non-uniformity arising

$$t = \frac{\rho \cdot Nu \cdot \sqrt{R_g T}}{\alpha \cdot P \cdot (c - b/T^2) \cdot (\Delta T / W)}$$

where α is the factor of condensation/evaporation, **Rg** is the gas constant, **Nu=ΔW/W**



Calculated time of fuel layer Nu=2% arising.

Assumption: initial Nu=0, factor of condensation α=0.5

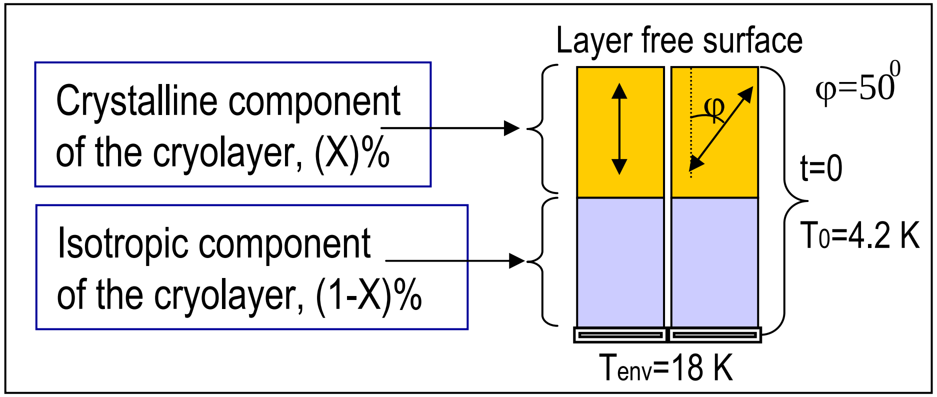
Target parameters: ICF target ∅1 mm, W=5 μm ; CHGT-1 ∅4 mm, W=200 μm

Target delivery (symmetrical heat flow). Layer degradation due to anisotropy of fuel material.

The rate of heat conduction in the molecule crystals is proportional the sound wave velocity in this matter. Let us consider the coarse-grained fuel layer with random orientation of crystalline axis. At the beginning of the process of target heating, the anisotropy of sound wave propagation ($\Delta V/V_{av}$ ~19%) will lead to non-uniform temperature distribution along the layer free surface.

Task:

Estimate the temperature difference ΔT arising on the free surface of two crystallites with mutually normal orientation of axis (as shown on the right).



Solution:

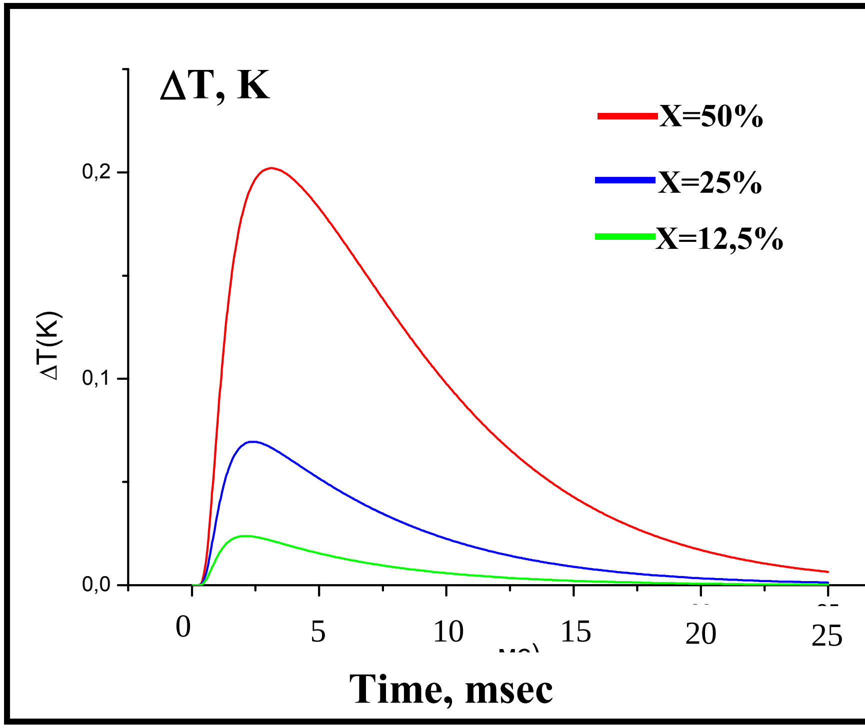
Thermal conductivity equations were solved for different relative composition of isotropic and crystalline phases in the layer: X- amount of crystalline component.

Parameters for solution:

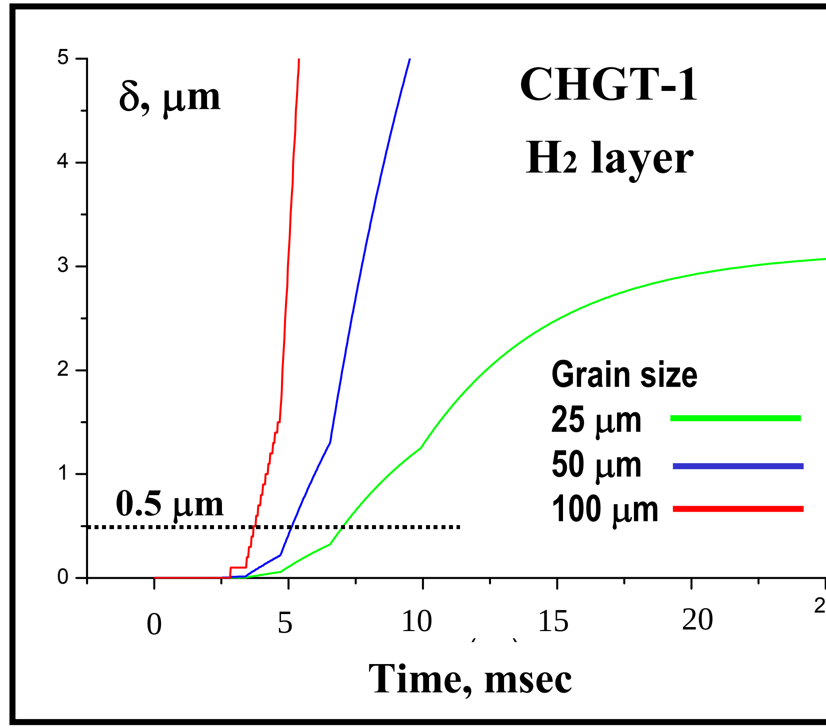
- sound velocity in single crystal: V_{max}=2230 m/s (along the main axis), V_{min}=1840 m/s (50 deg. to main axis), $\Delta V/V_{av}$ ~ 19% (data for H_2)

- Initial conditions: layer initial roughness is δ=0, layer initial temperature is 4.2 K, temperature of the environment is always T_{inv}=18 K. It is assumed that the heat removal from the layer free surface is ~0.

Estimations showed that layer degradation goes the quicker the larger size of crystal grains. For CHGT-1 and crystal grain of 25 μm the surface roughness of 0.5 μm arises for the time ~ 7 ms.



Evolution of temperature non-uniformity on the free surface of solid H2 layer



Evolution of free surface roughness

RESUME: to prevent the layer surface degradation it is necessary for solid layer to be completely isotropic

Requirements of minimizing a fuel layer mechanical and heat destruction during target delivery

- The major conditions for cryotarget quality survival during acceleration, injection and delivery into the burn area are as follows:
  - minimization of the temperature non-uniformity onto the free layer surface
  - minimization of the target injection temperature

- Slow down of the fuel migration due to the temperature gradient onto the inner layer surface can be achieved by means of:
  - introduction of gaseous helium into the target cavity
  - introduction of minor dopes of higher-melting components (such as T_2 or Ne) into the fuel composition

- To prevent (or minimize) the growth of surface roughness and thickness variation of the layer it is necessary for the solid fuel to be completely isotropic.

Formation of a fuel layer with the long-living parameters is the necessary requirement of IFE target technology

- Fuel layer parameters:

Theoretical requirements to fuel layer quality in the direct drive targets ➡ Nu < 2%, $\delta < 0.1 \div 1$ μm

- Fuel layer properties ensuring its long-living and survival during delivery process:

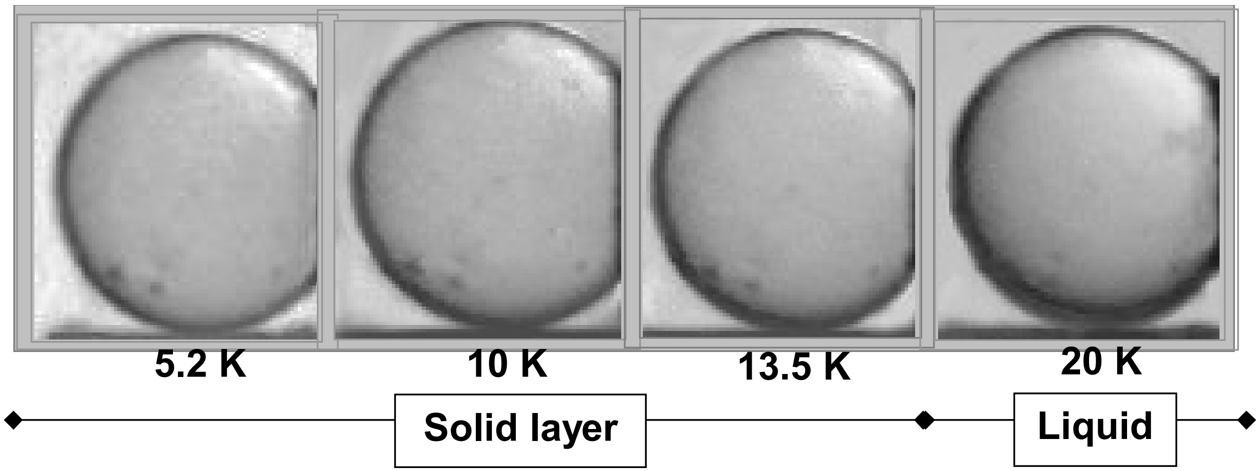
These properties allows to form fuel layer with the long-living parameters ➡
- Isotropy
- Resistance to heat load
- High tensile strength

Concept of a long-living fuel layer formation

- **Enhanced FST-layering ⇒ 3 stages technique for formation of a fuel layer with long living parameters:**

1. FUEL FILLING → Introduction of minor dopes into the gaseous fuel
2. FUEL MIXING → Gas-liquid transition due to drop-wise condensation by a volume
3. FUEL LAYERING → Rapid freezing and symmetrization based on FST-layering technology

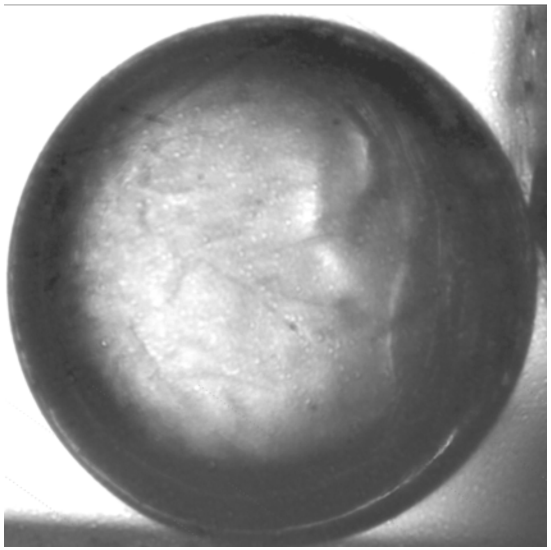
- **DEMONSTRATION.** New technique was demonstrated experimentally for glassy and CH shells filled with H_2+dopant (0.3- to- 9% HD, D2) and D_2+dopant (3% and 16%Ne)



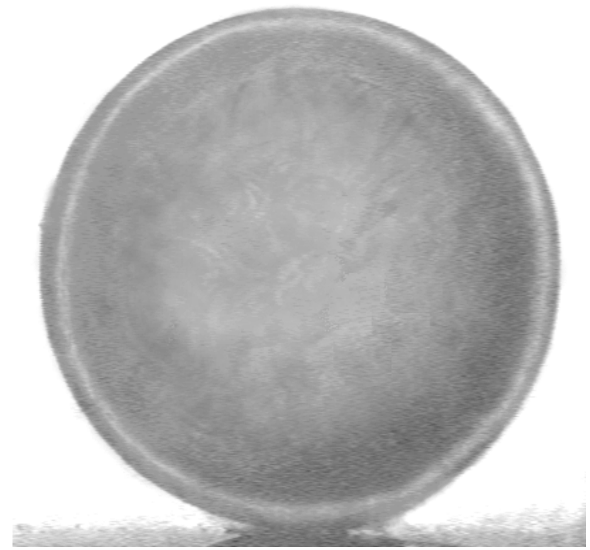
Transparent layer from H_2+5%HD does not transform into coarse-grained crystalline at target heating in the range of 5 K to T_{tp}

FST-layering inside CH shells with ∅ > 1 mm using new concept

Modified layering module



CONDITIONS OF THE EXPERIMENT
Modified layering module
Outer coating: 150 Å Pd
CH shell: ∅1.2 mm
Solid layer: 44 μm, H_2 + dopant (5%HD)



CONDITIONS OF THE EXPERIMENT
Modified layering module
Outer coating: 200 Å Pt/Pd
CH shell: ∅1.5 mm
Solid layer: 50-μm, D_2+dopant (3%Ne)

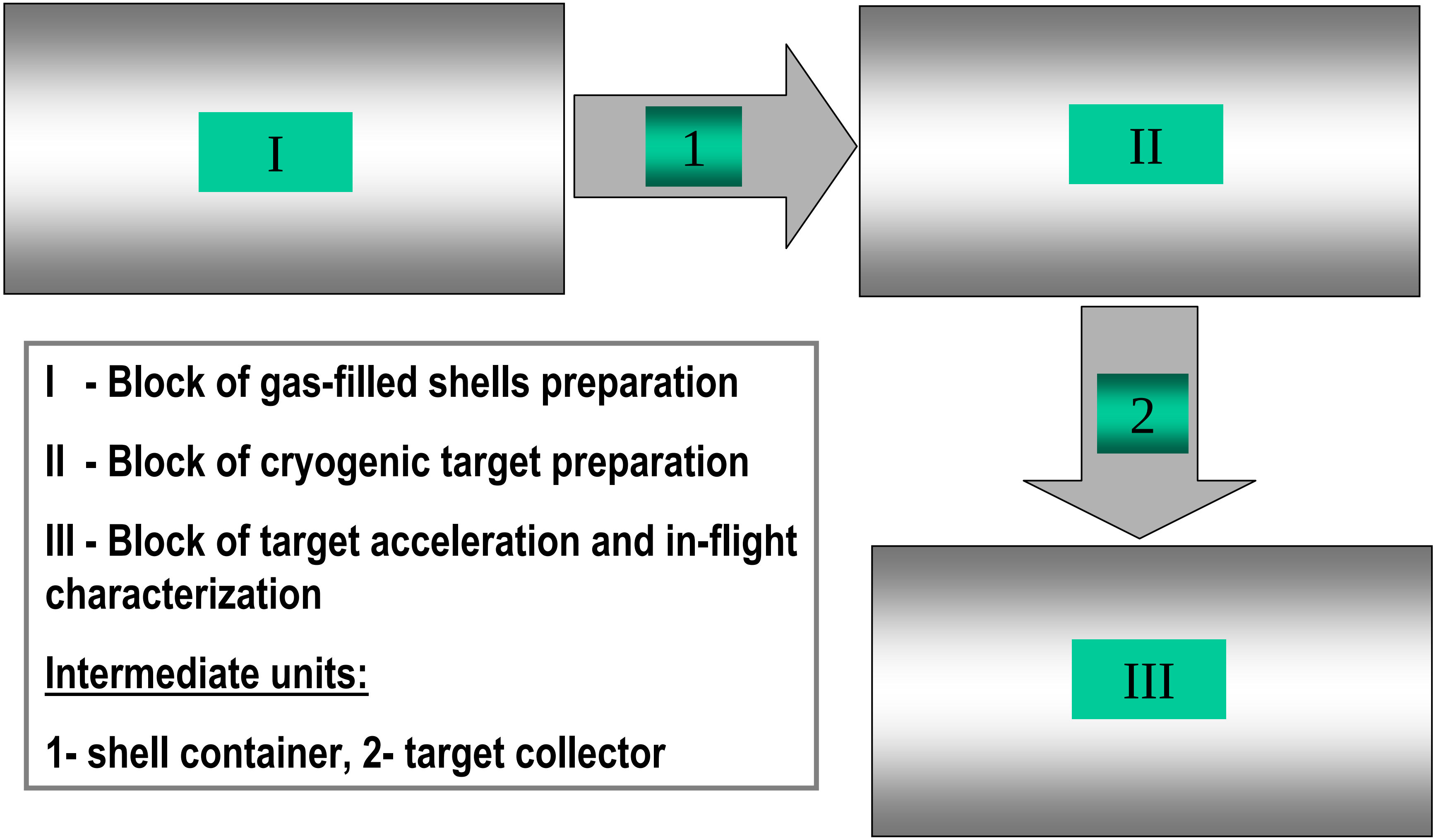
The FST technologies are useful for IFE target factory because they ensure the following:

- Rapid layering of reactor-scaled targets
- Formation of a layer with long living characte-ristics of quality using the enhanced FST-layering
- Repeatable target formation & injection
- Considerable minimization of tritium inventory in all subsystems

Proposal for creation of a target factory prototype. Task setting.

- **PURPOSE: Finding the technically suitable solution for the key elements of the IFE target factory.**
- **DESIGN REQUIREMENTS:**
  - Cryogenic target formation and injection with a rep-rate up to 1 Hz
  - Target parameters: CH shell OD=4 mm, $\Delta R=45$ μm, W=200 μm (Nu $\leq 2\%$, $\delta \leq 0.1$ μm)
  - Creation of a fuel layer with the following properties: isotropy, resistance to heat load, high tensile strength
  - Tritium inventory minimization
- **SPECIAL FEATURES OF TECHNICAL APPROACH:**
  - Work with a batch of free-standing shells at each production step
  - Rapid diagnostics of target quality (for the purpose of the preliminary and in-flight characterization)
  - Tomography data processing methods for target precise characterization
- **IMPLEMENTATION CAPABILITY:**
  - Free-Standing Target (FST) technologies and the upgraded FST facility (created at LPI)
  - Experience gained at LPI, RSSE (Moscow) and SPU (St.Petersburg) under development of electro-magnetic, gravitational and gas guns
- **COLLABORATORS IN RUSSIA: Lebedev Physical Institute (LPI, Moscow), Red Star SE (RSSE, Moscow), State Polytechnic University (SPU, St.Petersburg)**

Main building blocks of a target factory prototype



I - Block of gas-filled shells preparation

II - Block of cryogenic target preparation

III - Block of target acceleration and in-flight characterization

<u>Intermediate units:</u>

1- shell container, 2- target collector

Building blocks, main subsystems and interface units

I. BLOCK OF GAS-FILLED SHELLS PREPARATION (T=300 K)

1-Shell Tester, 2-Shell Container, 3- Fill System

II. BLOCK OF CRYOGENIC TARGET PREPARATION (T= 4.2-40 K)

1- Layering module, 2- FST Tester, 3 – Unit for protective cryolayer formation

III. BLOCK OF TARGET ACELERATION AND IN-FLIGHT CHARACTERIZATION (T=5-10 K)

1- Revolver, 2- Sabots feeder, 3- Unit for protective cover production, 4- Electro-magnetic accelerator, 5 - System for Rapid Diagnostic

INTERFACE UNITS:

1 - Shell container; 2 - Target collector.

MAIN ELEMENTS HAVE BEEN TESTED UNDER THE OPERATIONAL CONDITIONS

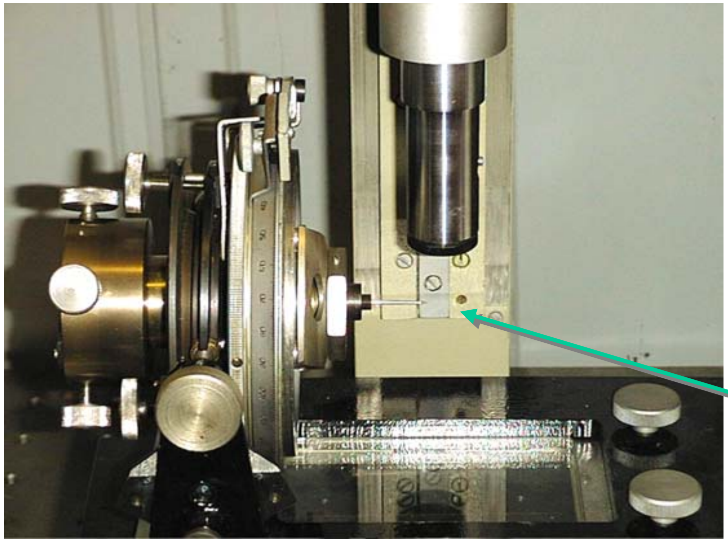
I.Block of gas-filled shells preparation.
Tomograph "Shell Tester"

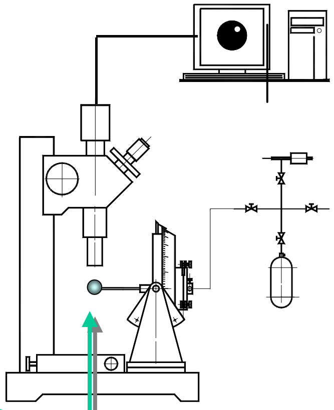
❑ **Application of the facility**

1. Microshells characterization
2. Reconstruction algorithms development and testing

❑ **Scanning Parameters**

- Full scanning angle: 360 deg.
- Number of projections (max) – 1000
- Positioning accuracy: ± 1.5 min

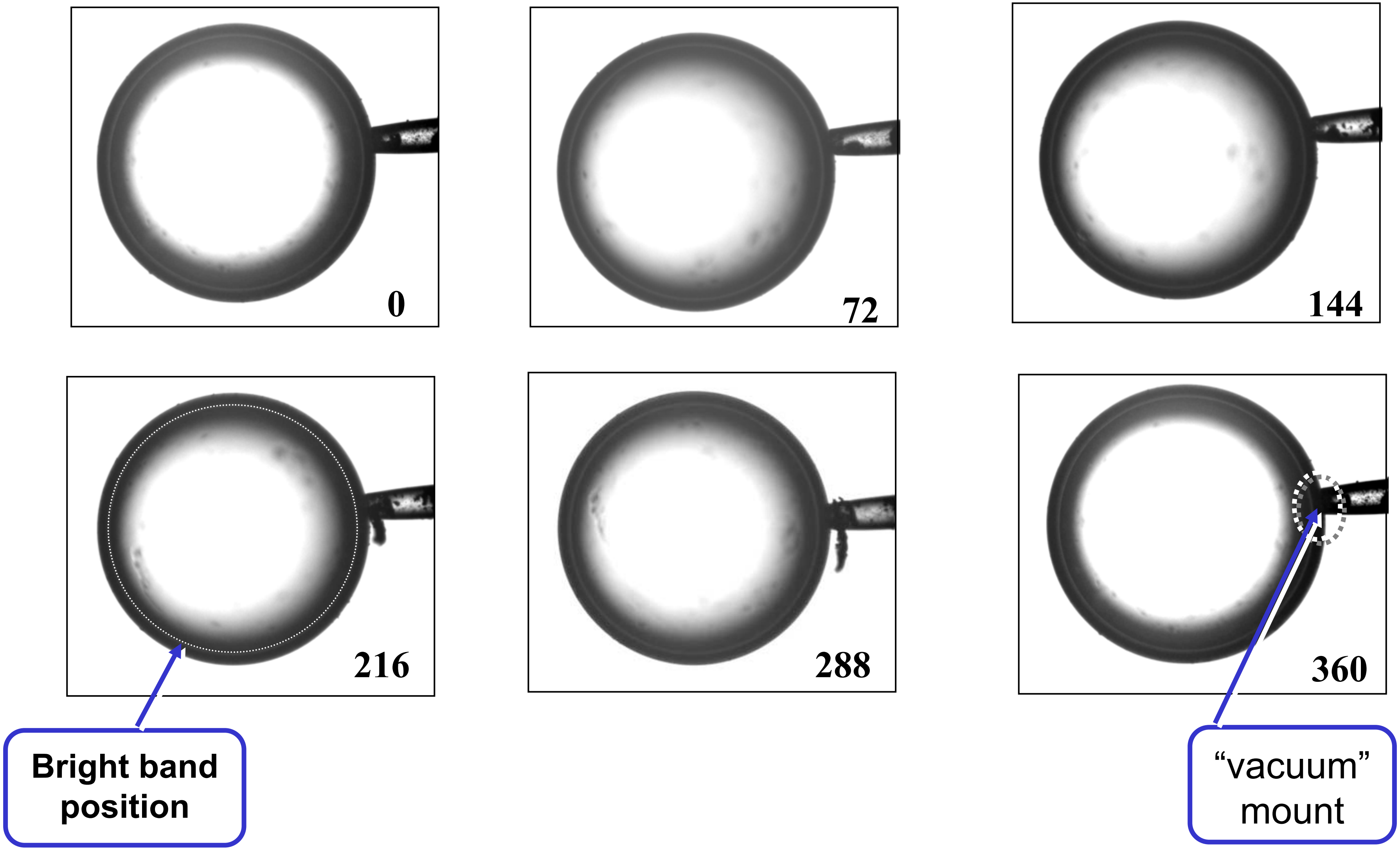




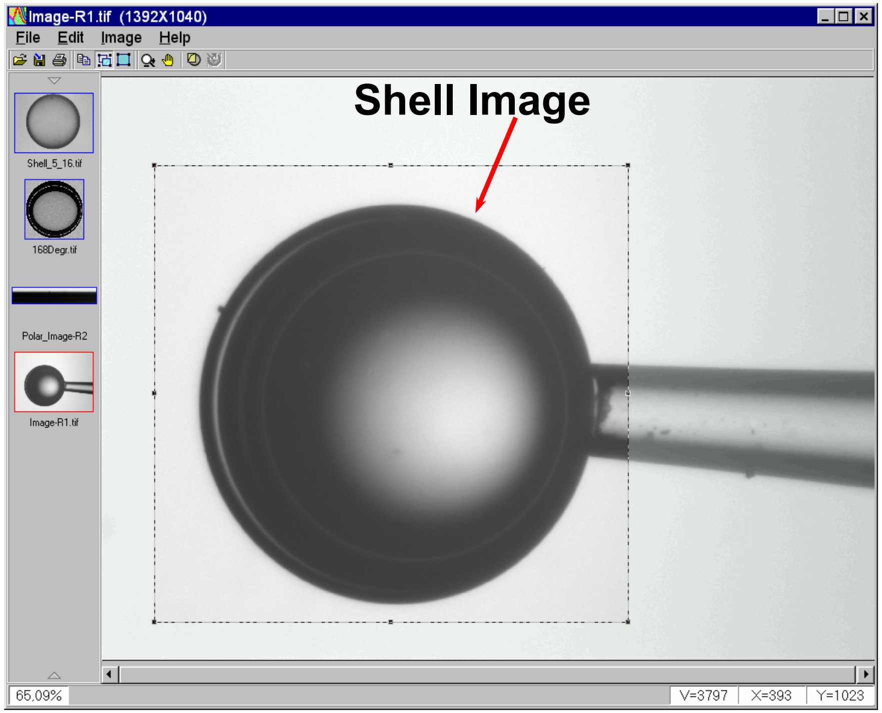
Shell positioning

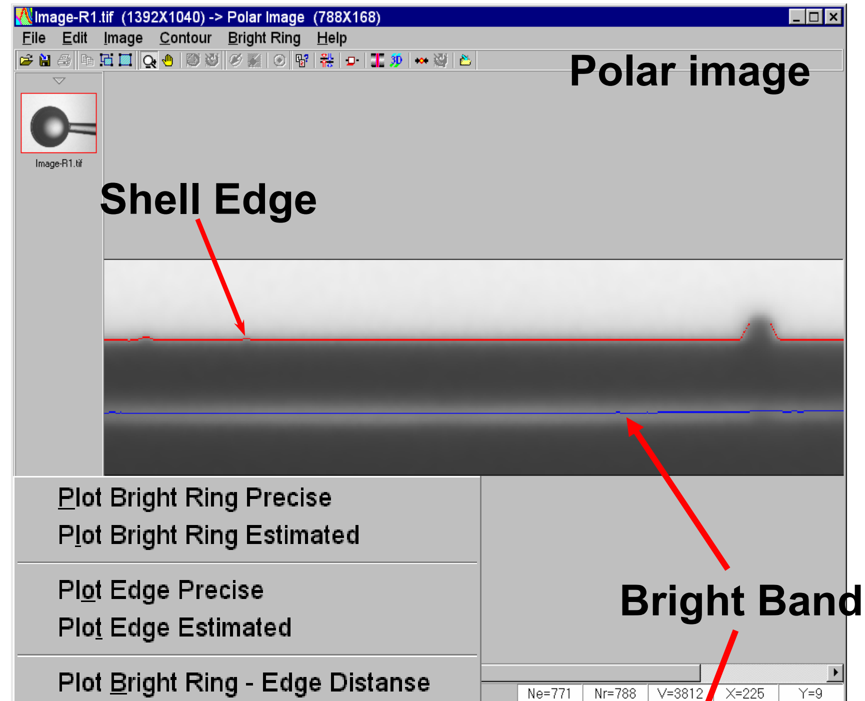
The facility is set up at LPI in 2001 under the ISTC Project #1557

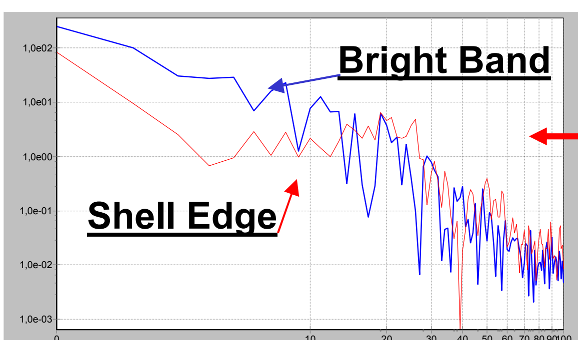
Tomograph Shell Tester: image projections data



"Bright ring new" program for exact identification of the coordinates of the bright band and of the shell edge on the backlit image of a target

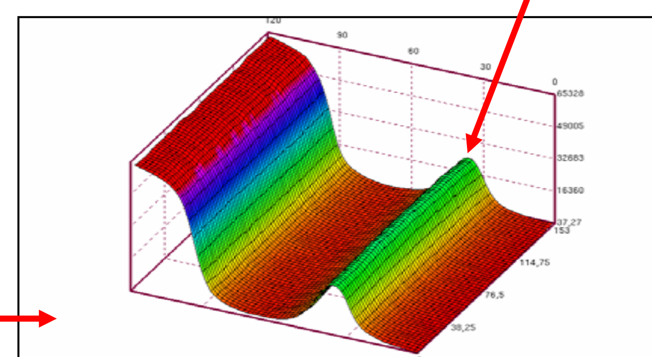






Power spectrum

3-D visualization

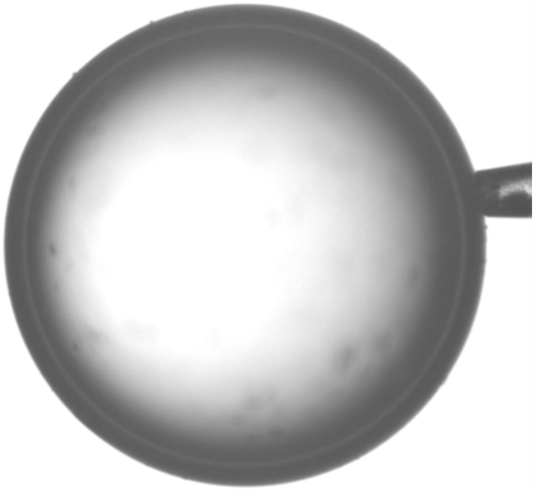


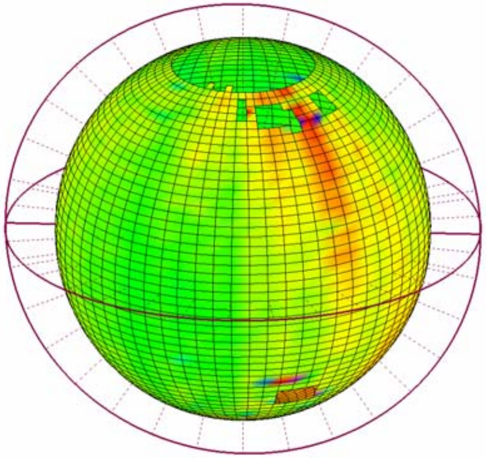
Tomograph “Shell Tester”. CH shell surface reconstruction using 100 projections data

SHELL PARAMETERS (reconstructed)

1.Shell's outer surface
- Mean radius :: 580,8
- Min radius :: 580,1
- Max radius :: 589,4
- Out of Round :: 0.8 %

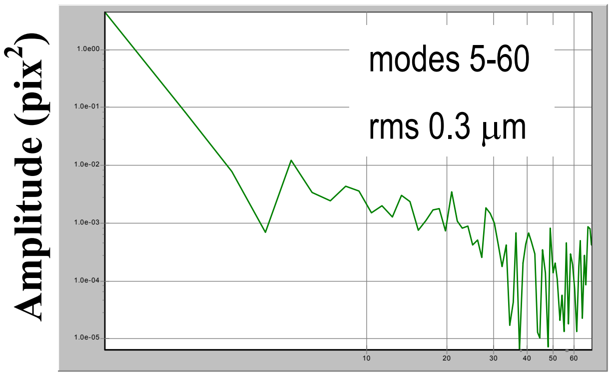
2.Shell's inner surface
- Mean radius :: 539,2
- Min radius :: 535,7
- Max radius :: 541,8
- Out of Round :: 0.6 %



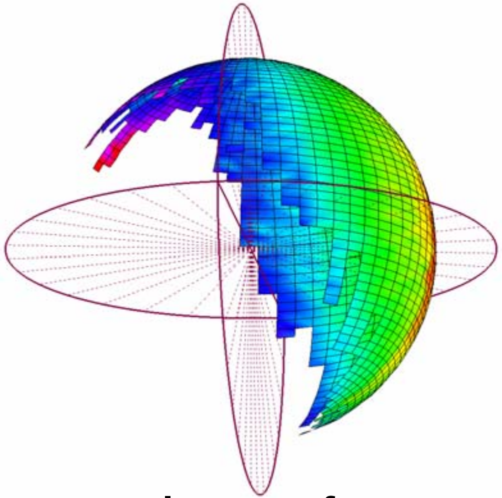


Outer surface

The bright band power spectrum



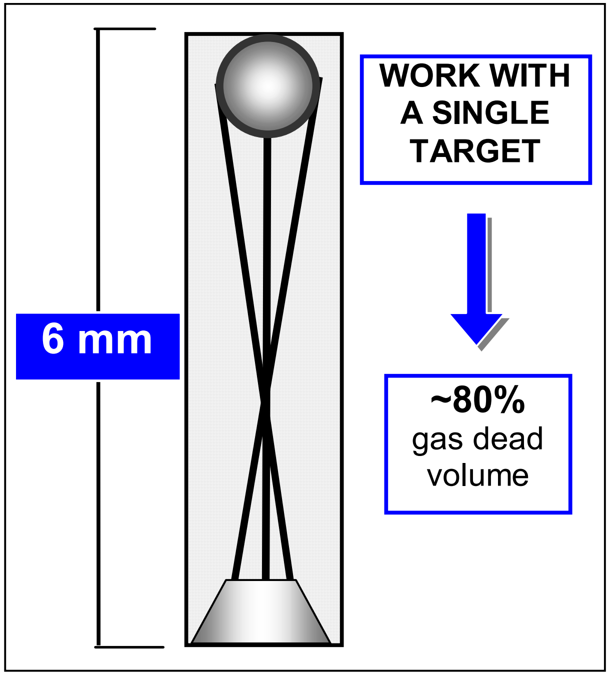
Mode number



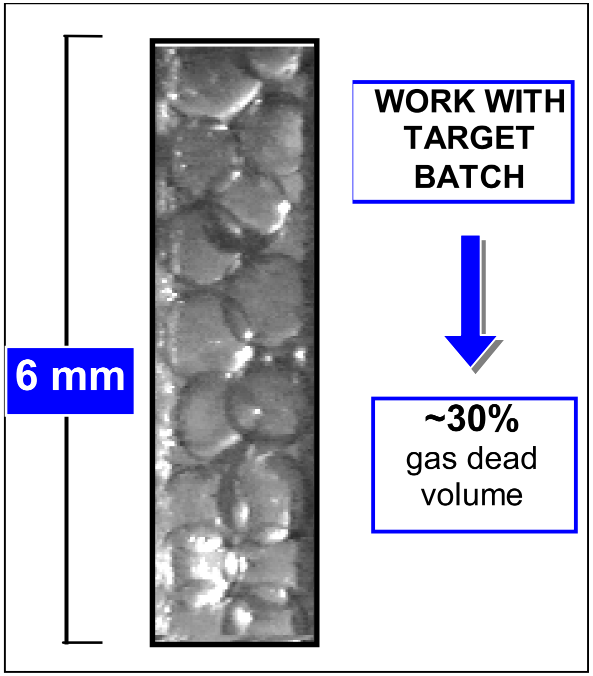
Inner surface

I. Block of gas-filled shells preparation.

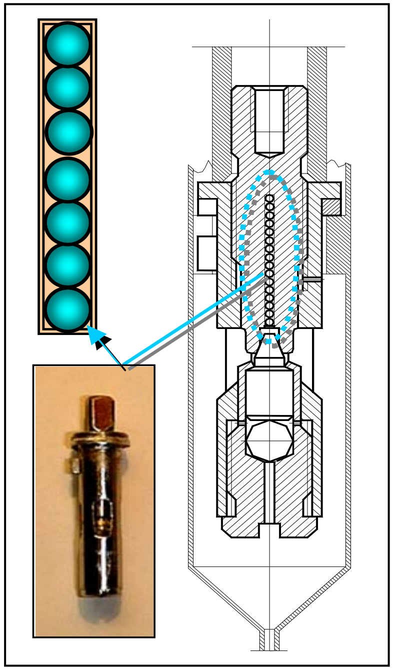
Shell container: 5-to-25 shells inside 1 container



PRE-MOUNTED TARGET APPROACH



FREE-STANDING TARGET APPROACH



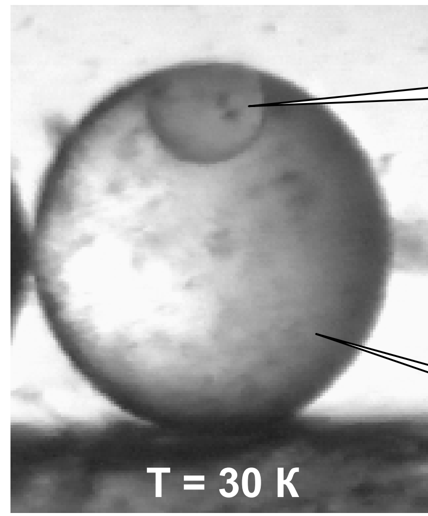
Shell container diagram and general view

Shell container application at the stage of fuel-filling gives the following advantages as regard to the conventional approach (pre-mounted target):

1. Minimal filling time per 1 target; 2. Minimal dead volume of gas in shell container

I.Block of gas-filled shells preparation.
Fill facility

Results of the Facility Testing



Vapor bubble

CH shell, ∅ ~ 1 mm
P_F= 850 atm (300K)

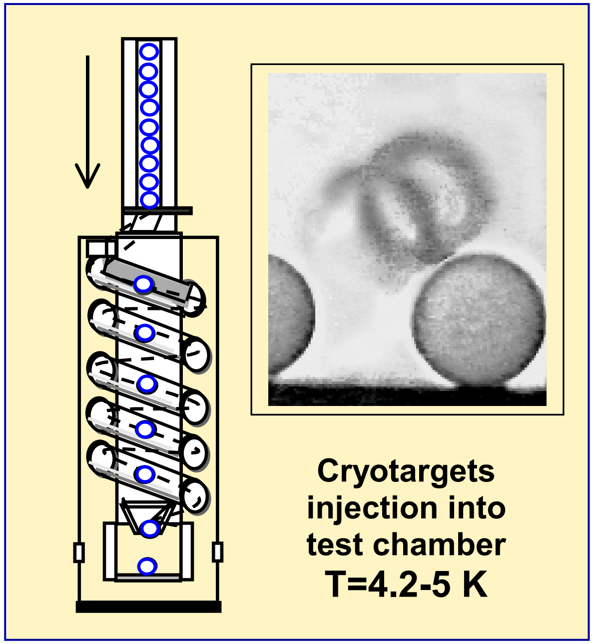
Liquid H_2

Computer aided fill facility for diffusion filling of CH shells with gaseous fuel to $P_F \leq$1000 atm at 300 K. Started up at LPI in 1998.

To obtain the required fuel mass inside a 4 mm diameter reactor target with 200-mm-thick fuel layer it is necessary to fill it up to 423 atm of D_2 (or 430 atm of DT) at 300 K. This means that we can use our facility for filling the reactor-size shells with a fuel.

II. Block of cryogenic target preparation
Layering module

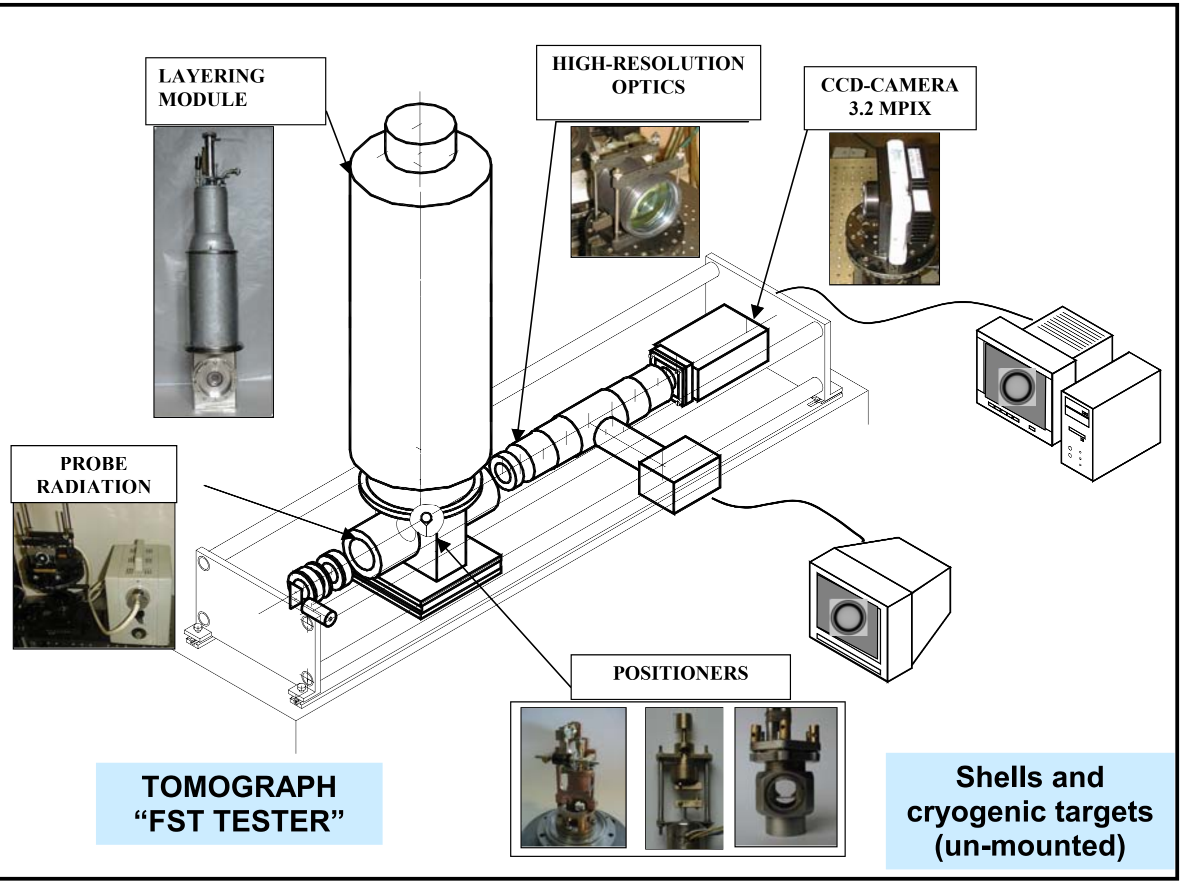
- Shell container is used for transporting an array of filled shells from the filling system into the layering module at 300 K
- A new layering module will be used for fabrication of classical high gain targets consisting of a 4 mm diameter CH shell with a 200-μm- thick D2-fuel layer.
- Layer formation is based on the FST-layering techniques.
- The fabricated cryogenic targets will be injected into the optical test chamber for characterization.



Optimization of fuel layer formation is one of the important activity trends

The layering channels of different shape and size are plan to use for the FST optimization

II. Block of cryogenic target preparation.
Tomograph FST Tester
(under way in the ISTC pr.#1557)



❑ **Requirements to scanning scheme:**

- Target rotate around vertical or horizontal axis
- Cryostat, lighter and CCD are fixed
- Probe radiation: non coherent visual light

❑ **Realization:**

- Probe radiation wave length: 0.49 μm
- Imaging system spatial resolution: 1μm
- Micro-positioning devices for free-standing target rotation
- Work temperature: T$\geq$ 4.2 K
- Number of projections, max: 100 (currently)

Results of the hard&soft ware joint operation

Tomograph "FST TESTER".

Un-mounted shell surface reconstruction using 60 projections data

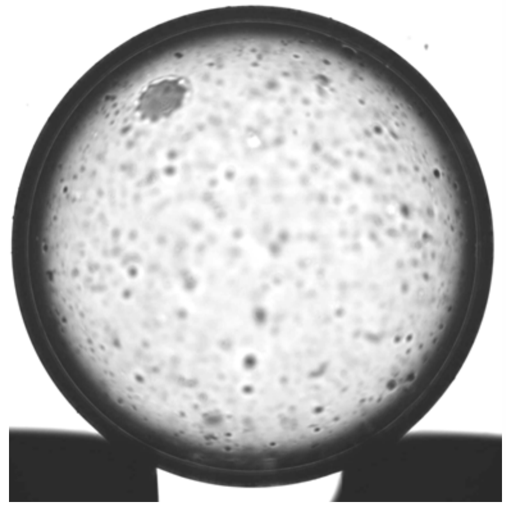
SHELL PARAMETERS
(reconstructed)

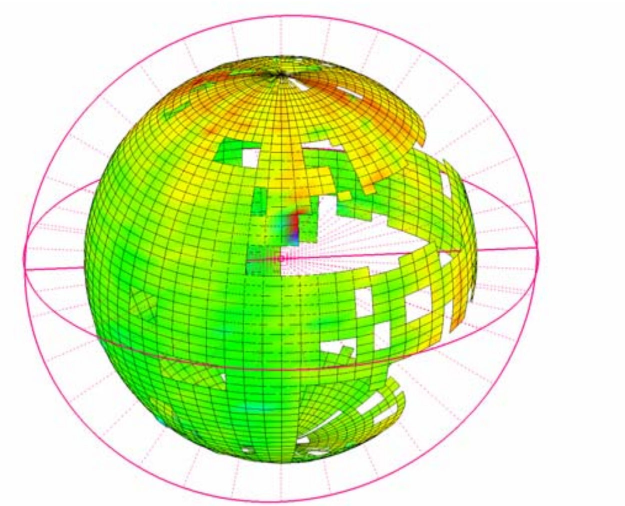
1.Shell's outer surface

- Mean radius :: 1138.9
- Min radius :: 1138.1
- Max radius :: 1150.1
- Out of Round :: 0.5 %

2.Shell's inner surface

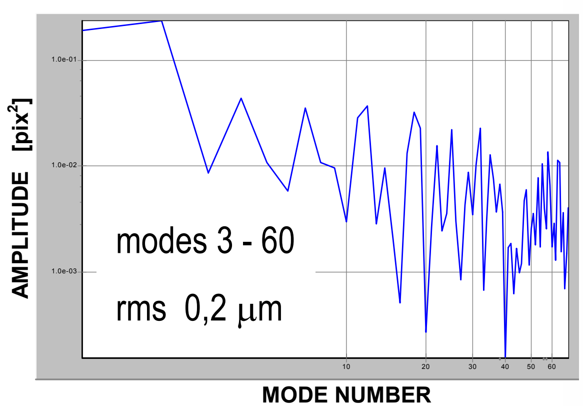
- Mean radius :: 1109.8
- Min radius :: 1108.2
- Max radius :: 1101.5
- Out of Round :: 0.3 %

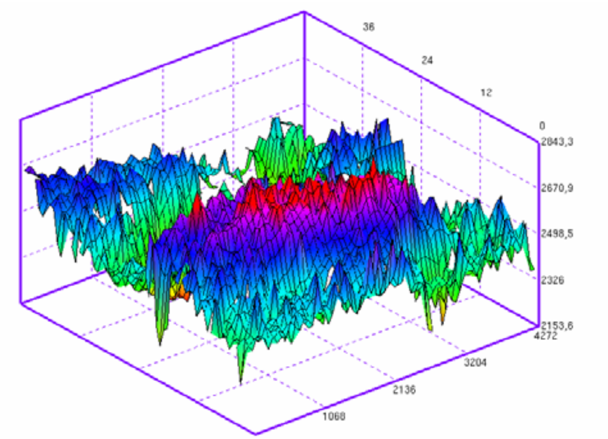




Outer surface

The bright band power spectrum





Inner surface

IAEA RCM, Vienna, Nov 4-7, 2003

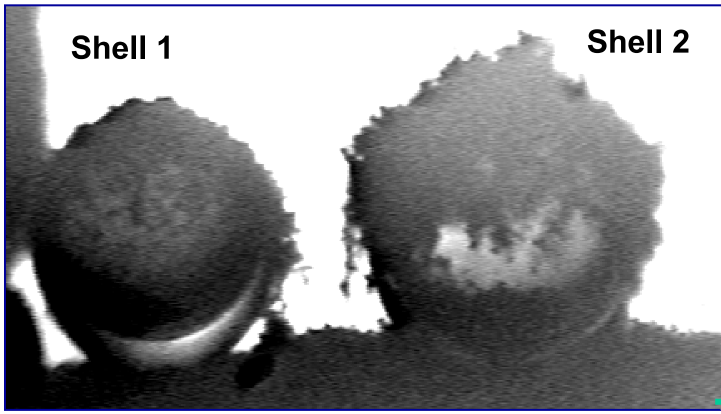
Testing with cryogenic targets is planned in March-April 2004 (ISTC pr.#1557)

II. Block of cryogenic target preparation.
Unit for protective cryogenic layer formation

- **Two polymer shells inside the R&B cell prior to the experiment, T=14.6 K**

Solid O_2

on the top



Shell 1:

2R=1.2 mm

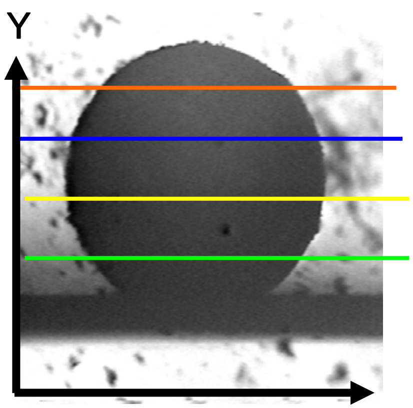
Shell 2:

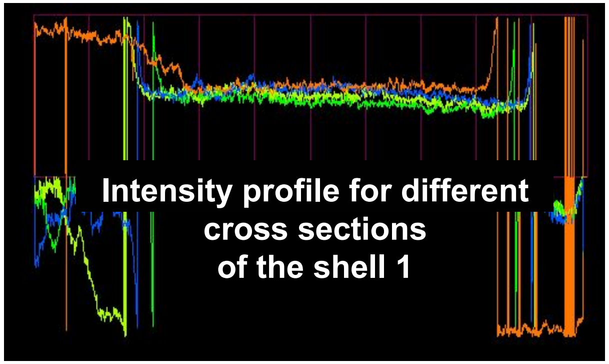
2R=1.4 mm

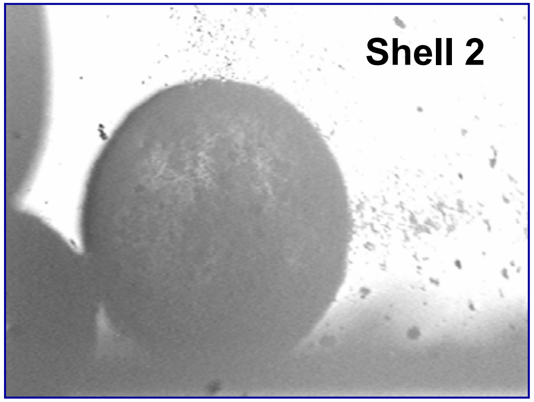
R&B cell

We suggest to use the R&B cell for producing the protective cryo-genic layer onto a target outer surface.

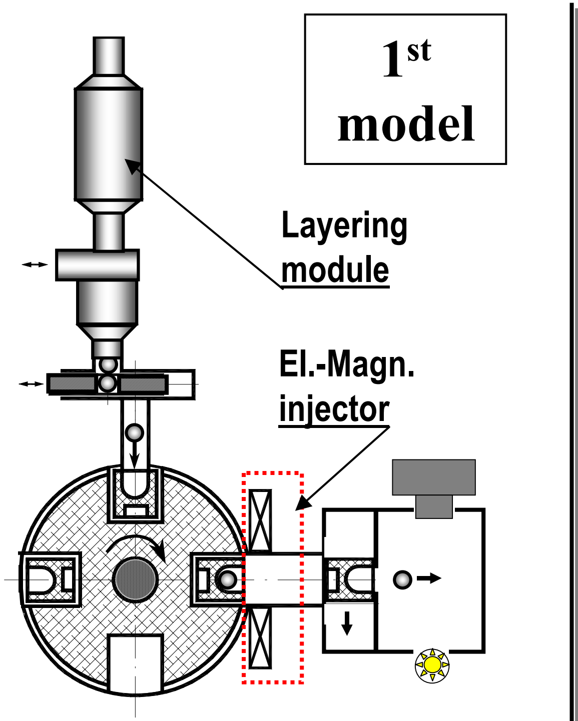
- **After Bouncing mode is generated in the R&B cell both shells are coated with opaque uniformly distributed protective layer (solid O_2), T=14.6 K**



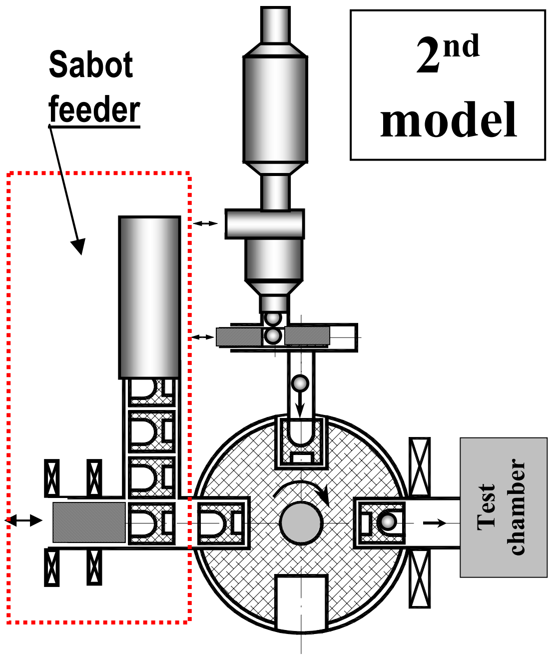


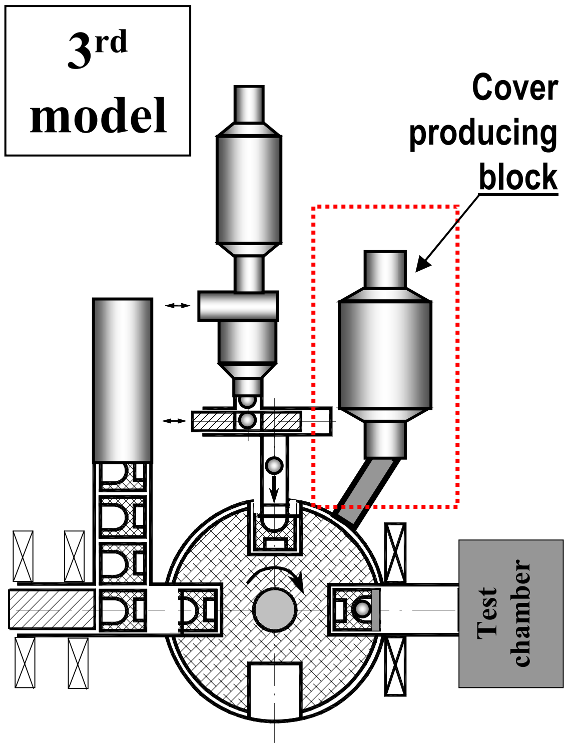


III.Block of target&sabot assembly and acceleration
(also serves for layering module/injector assembly)



Physical layout: see movie on the main page of
http://www.lebedev.ru/pages/cryotarget



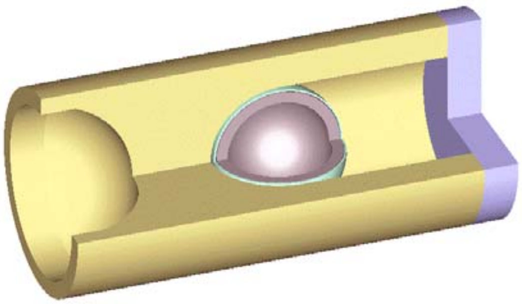


SABOT FUNCTIONS:

- **to transmit an impulse of motion to the target**
- **to protect the target from heat- and g- loads**

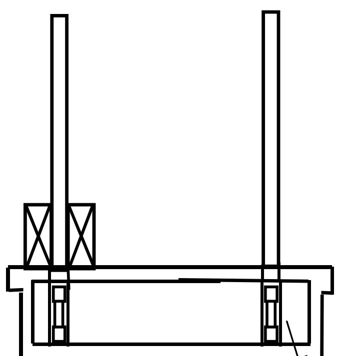
COVER FUNCTIONS:

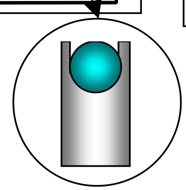
- **to protect the target from a head wind during its flight**



Mechanical models for testing the blocks of sabot+revolver and sabot+coil

MODEL #1

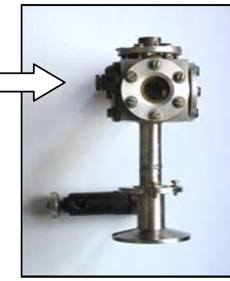


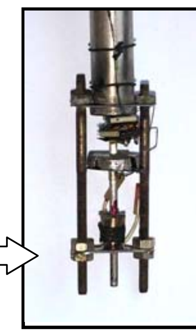


Revolver for sabot driving
General view and schematic

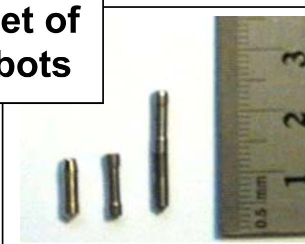
Optical test chamber

MODEL #2





A set of sabots



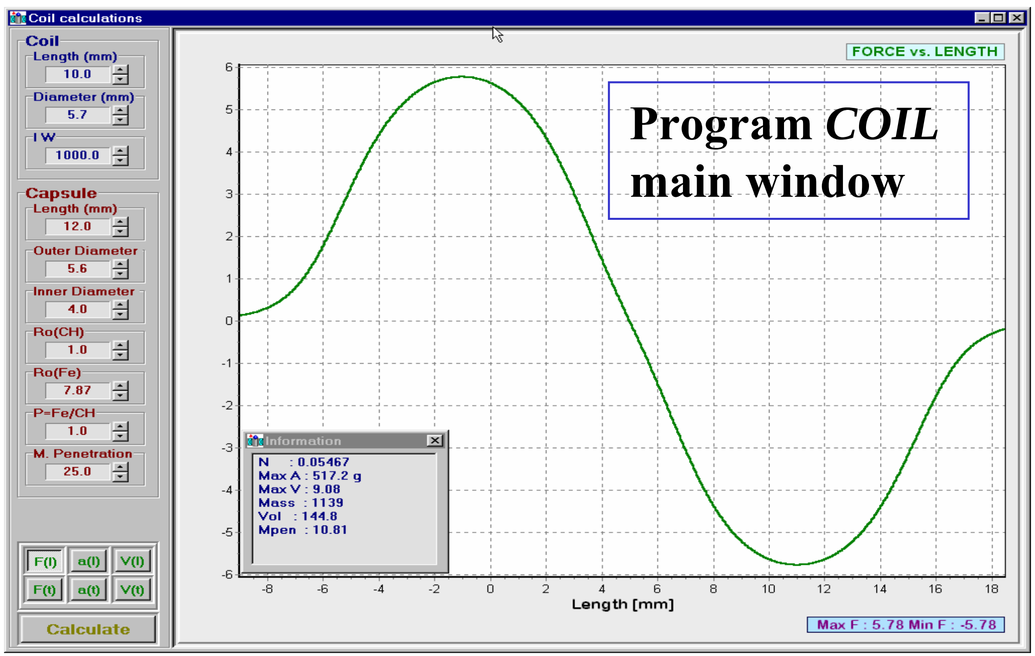
Mathematical model and software for optimization of the driving body design (sabot and pusher)

Ponder-motive force driving magneto-active body in the solenoidal magnetic field:

$$F(z) = -\frac{\pi \cdot \mu_0}{4 \cdot \left[N + (1-N)/\mu_E\right]^2} \cdot (I\omega)^2 \cdot \Phi(z, l_c, l, r)$$

$$\mu_E = \frac{\mu^P}{1 + \left(\mu^P - 1\right) \cdot N}$$

For $0.2 \le P \le 0.8$ and $P=1$



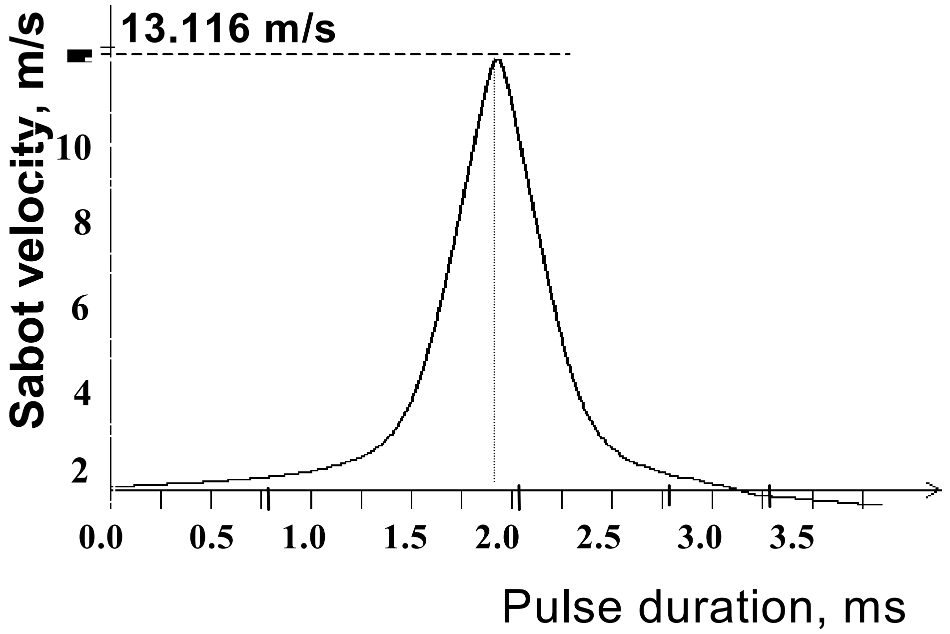
PARAMETERS OF OPTIMIZATION

- pusher and sabot material (ρ, μ, P)
- pusher, sabot and coil geometry (length, diameter)
- parameter I x ω
- current pulse duration

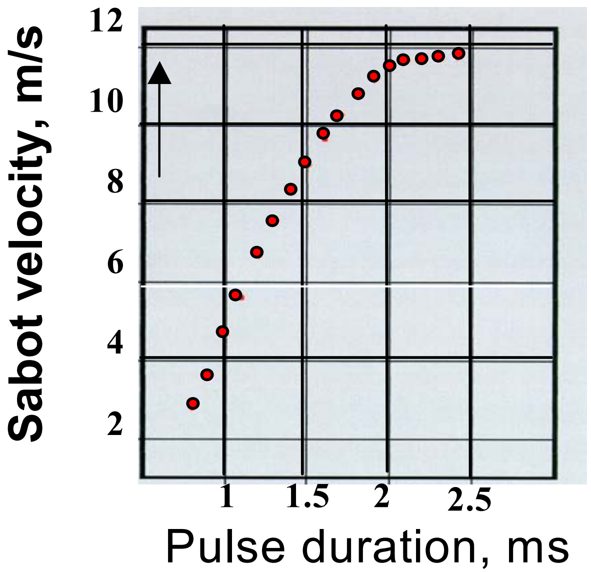
*/ P is the volume fraction of magneto-active additives into the polymer matrix

The estimated data and the experimental results for ferromagnetic sabot are in close agreement

T=300K, Jω=3500 A turn

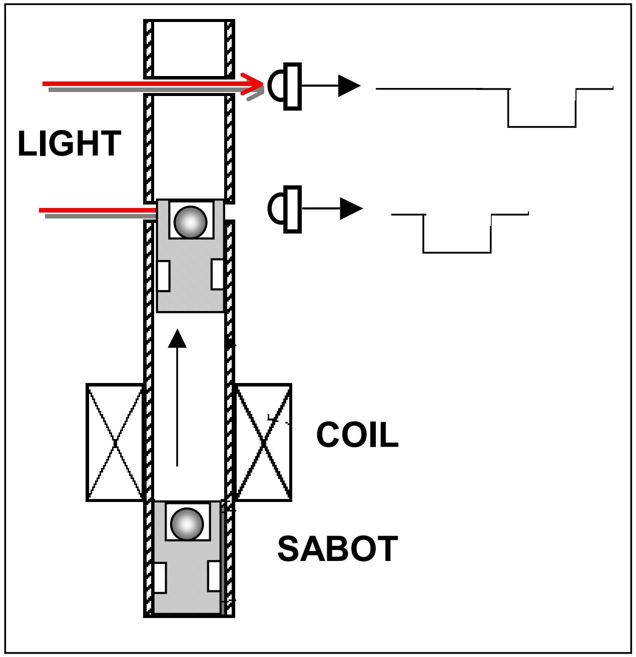


Calculated data

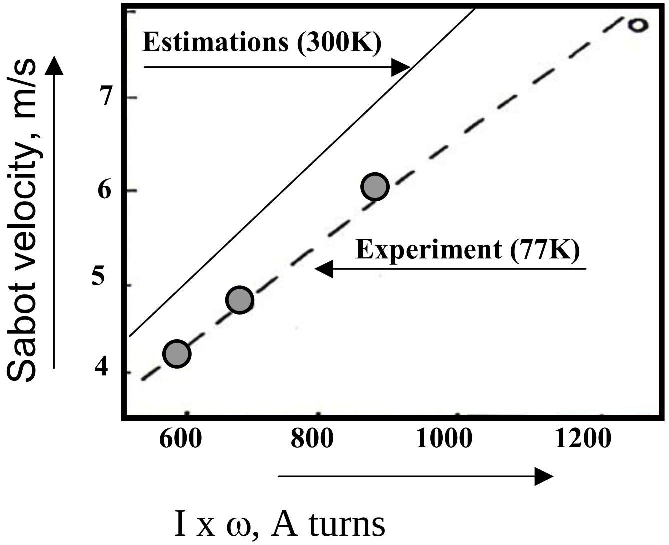


Experimental data

Sabot+target acceleration by the solenoidal field of a coil has been studied at room and cryogenic temperatures (ferromagnetic sabot)



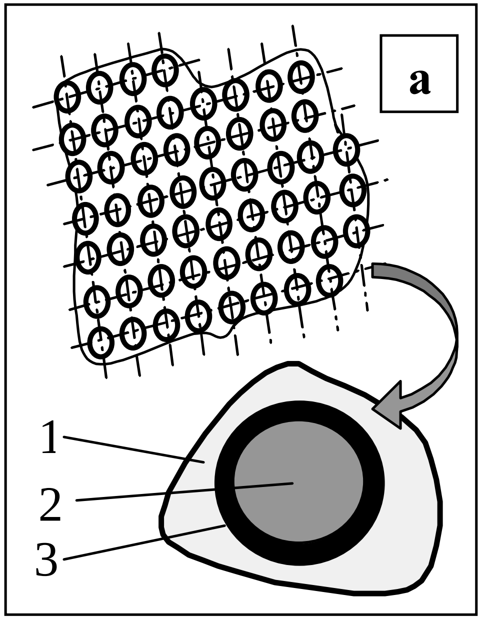
- **Coil**
  - I.D. 3 mm, Length studied 1, 2, 3 cm
  - Wire: Cu, ∅ 0.08 mm, 1000 turns
  - Temperatures studied: 300K, 77K, 4.2K
- **Sabot**
  - O.D. 2.6 mm, Length studied 1, 2, 3 cm
  - Magnetic penetration factor 250 (300K)
  - Target nest geometry: plane, cone

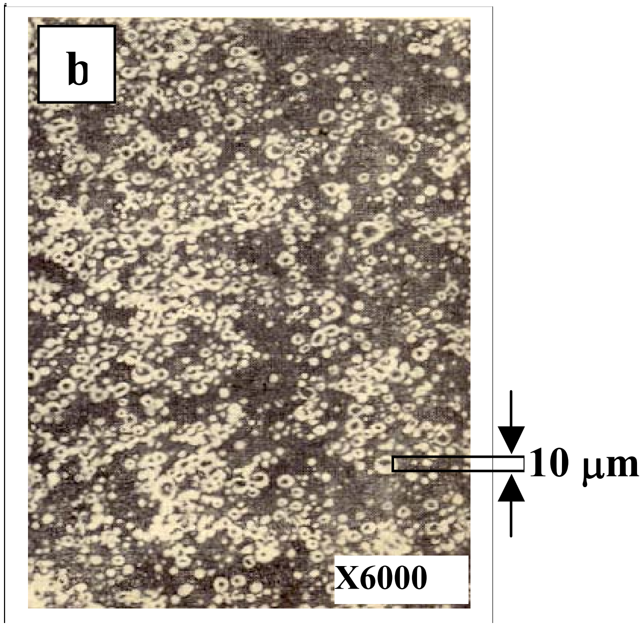


Comparative analysis of the calculation and experimental data has shown: magnetic penetration of sabot material is twice as less upon sabot cooling from 300 K to 77 K

Magneto-insulator as perspective sabot material

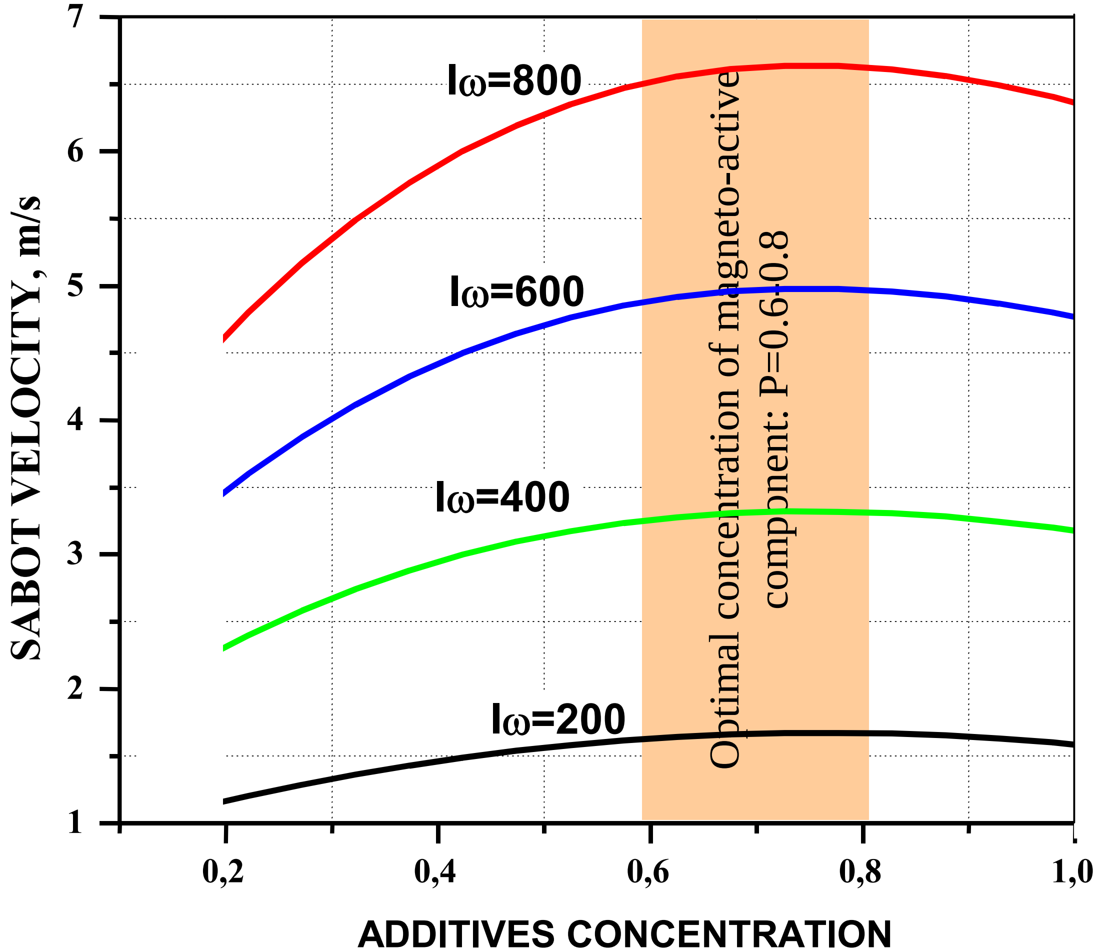
Application of magneto-insulator allows (1) to reduce eddy current, (2) to reduce sabot weight, and (3) to optimize the sabot material interaction with a solenoidal electro-magnetic field.





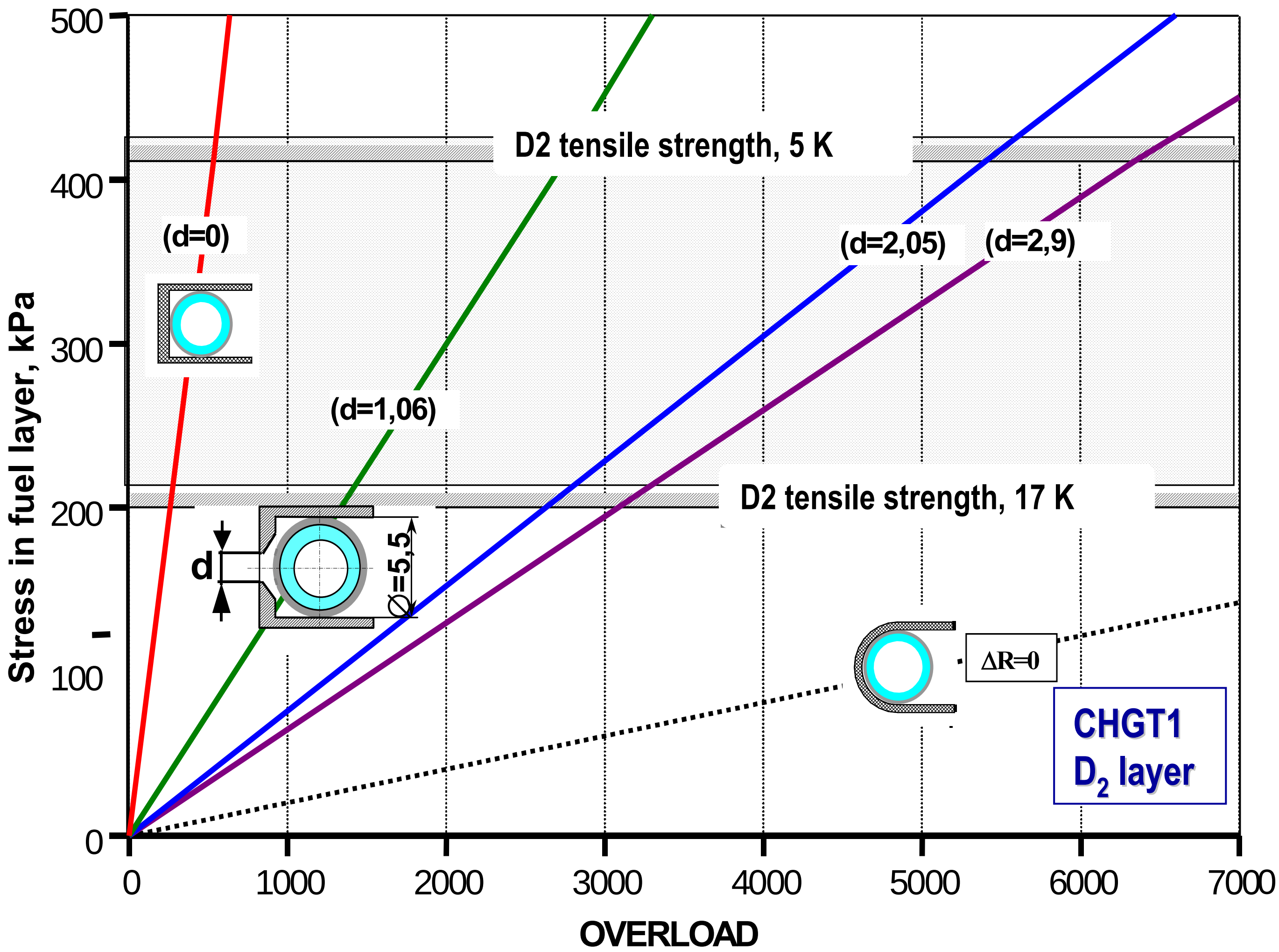
Magneto-insulator consists of polymer matrix (1) and magneto-active additives (2) covered by insulating layer to reduce eddy current (3); (b) X-ray image of magneto-insulator

Optimal concentration of magneto-active additives is in the range of 60-80% (calculations using program COIL)



- Parameters of calculations:
  Sabot made from magneto-insulator is 7 mm in length, 5.6 mm in diameter, density of additive material (Fe) is 6.5 g/cm^3, density of foam polymer matrix (CH) is 0.5 g/cm^3, effective initial magnetic permittivity is 125. Coil length is 10.5 mm, inner diameter is 5.7 mm.

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 material during the acceleration process.



RESUME.

The shape of the target nest in the sabot play an important role for target injection without mechanical damage and allows to reduce significantly the overall dimensions of the accelerator.
Technologically, the flat bottom with center hole has much promise than the semi-spherical one.

Rapid characterization of target parameters

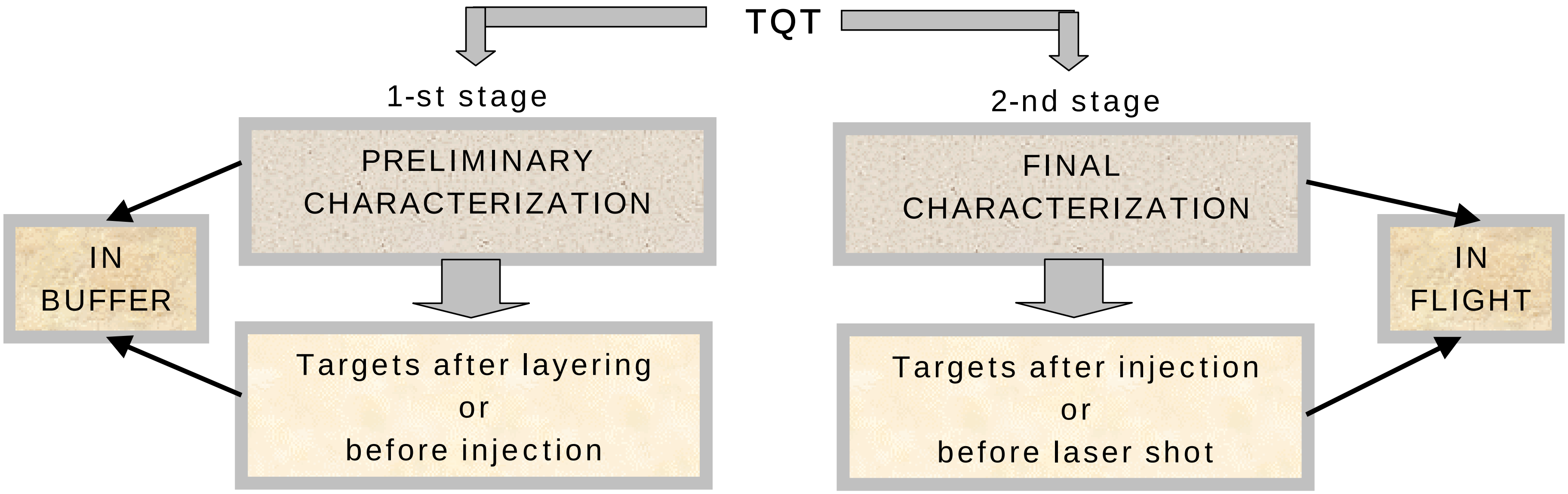
- Rapid diagnostic of target quality

- Target timing and tracking

Threshold target characterization

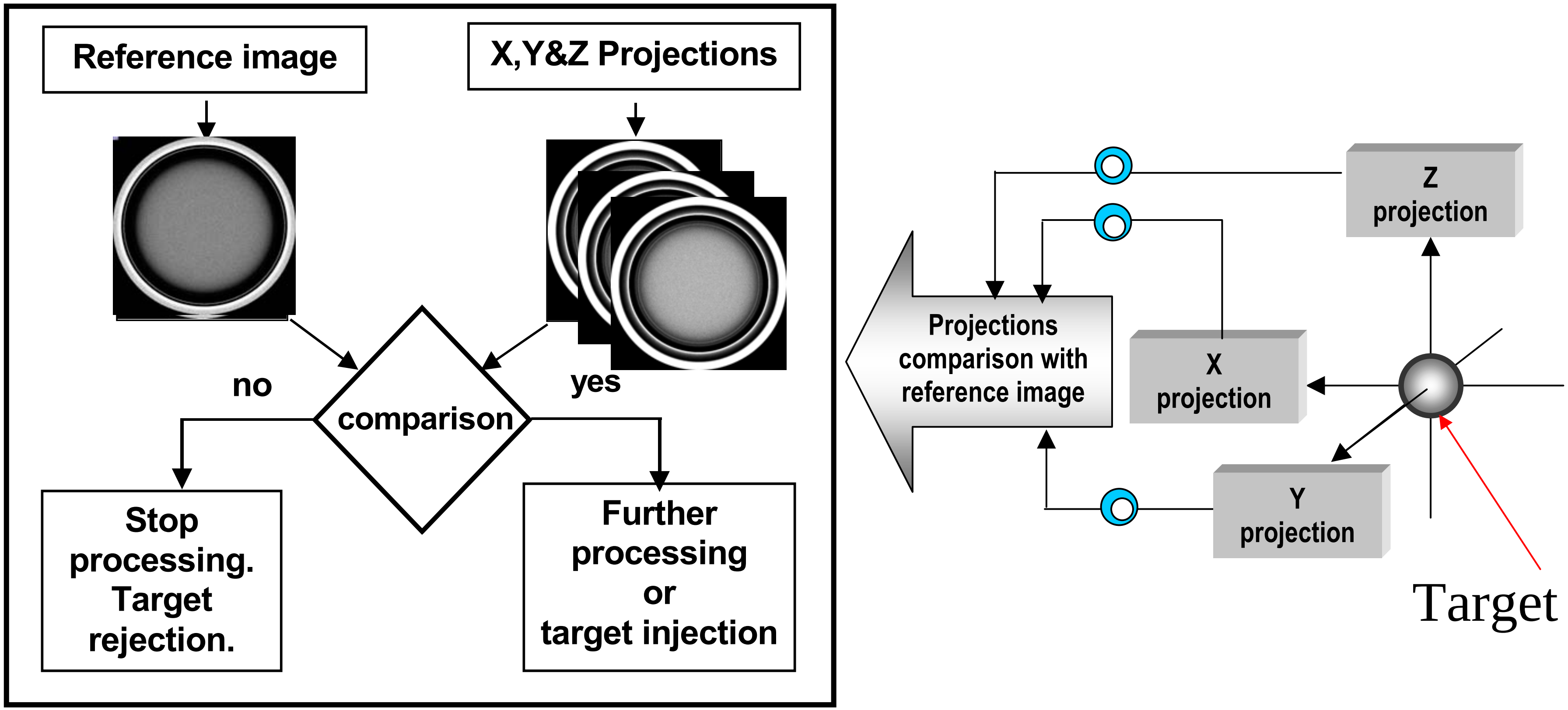
- A target quality thresholding (TQT) is based on the development of a new class of algorithms, which allows only establishing that target symmetry does not meet the specifications.

- Generally, the TQT can be used in both stages: fuel layering techniques development and fueling of a commercial power plant



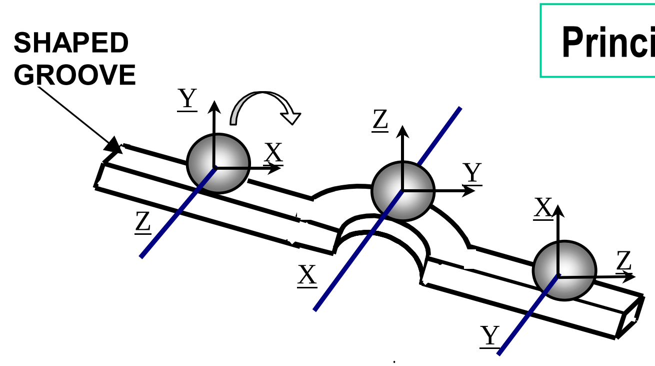
The TQT for the second stage requires the development of the facility for studying target survival during the injection process under the excess heat and the overloads

Principle of threshold characterization

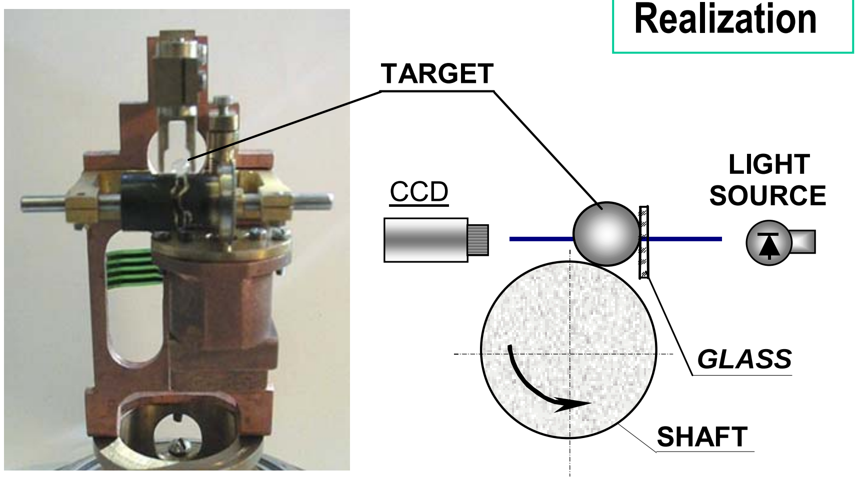


Schematic of target projections observation and comparison with the reference image (ideal target).

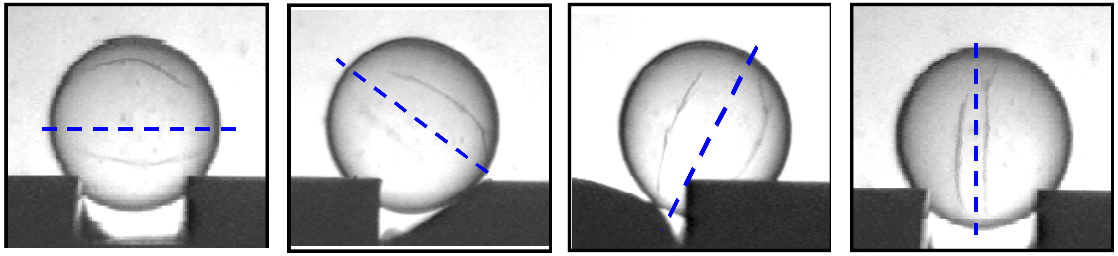
Target positioning device which is currently used at LPI for precise and threshold characterization



Changing the target rotation axis under its movement along the guiding groove



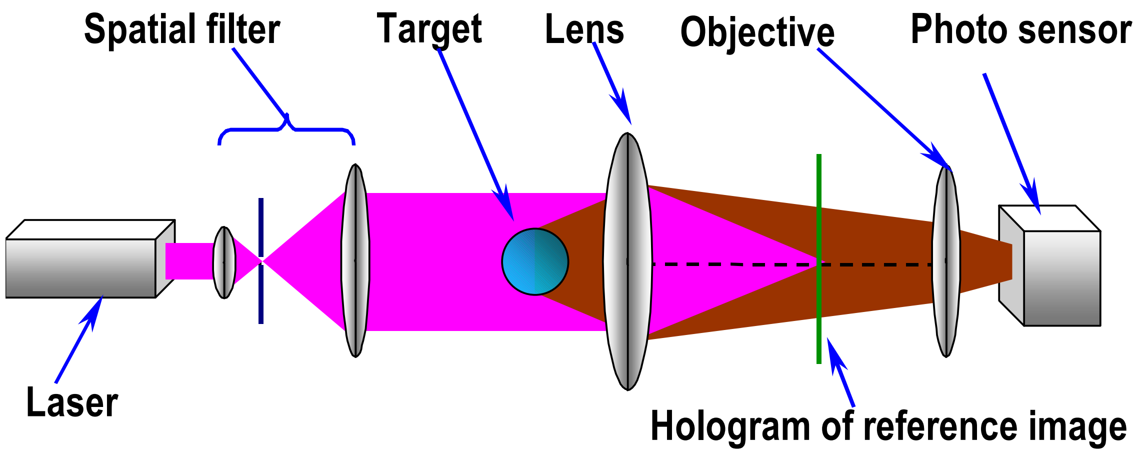
Present status	
Number of projections:	3-to-100
Work temperature:	300-to-4.2 K
Positioning accuracy:	± 4 minutes



Shell rotation along the shaped groove

Rapid control of target quality using holography method of image recognition

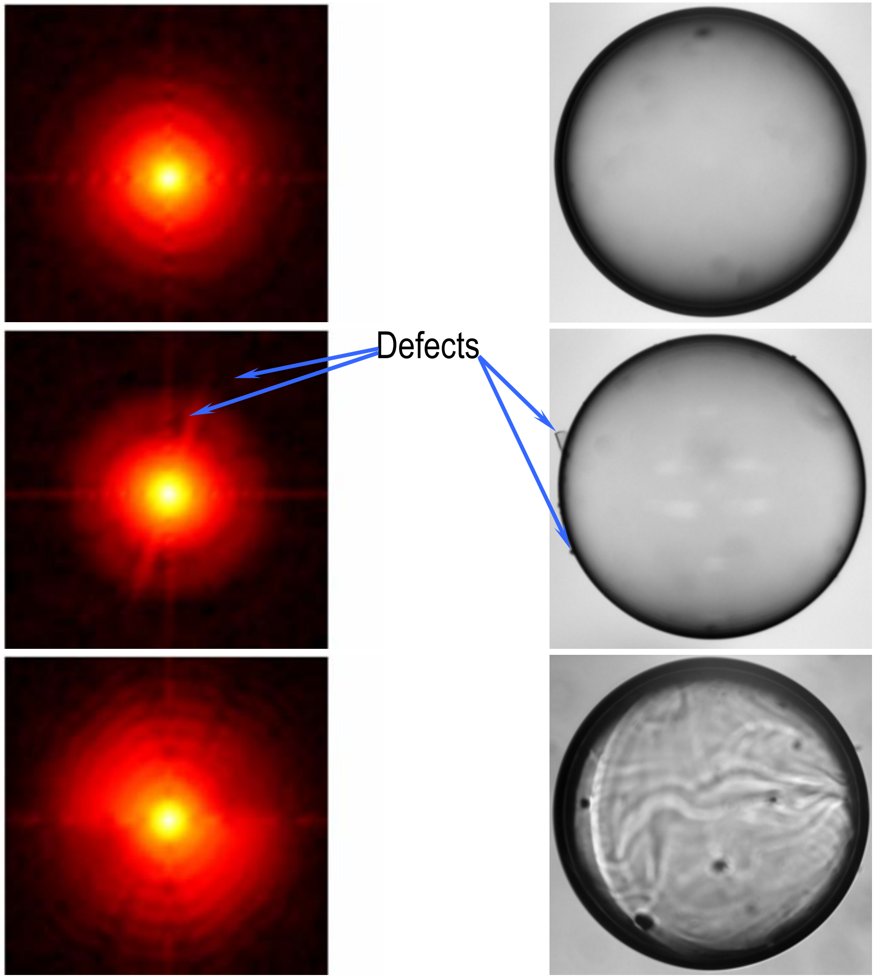
The recognition signal is proportional to the correlation between the real and the reference images



- Objective performs the Fourier inversion of the product of the Fourier transform of input signal and the Fourier transform of reference image (i.e. target of ideal quality) recorded in the filter.
- Then the light passes to a photo-sensor (single photo-detector). The recognition signal is greater in the case of better conformity between the real and the reference images (signal/noise ratio is maximal)
- A combination of simple electrical threshold circuit and actuating unit provides easy selection of targets.

- Actuating unit and photo-detector only determine the operation rate of such a system (several μsec)
- Signal/noise ratio is maximal in the case of good conformity

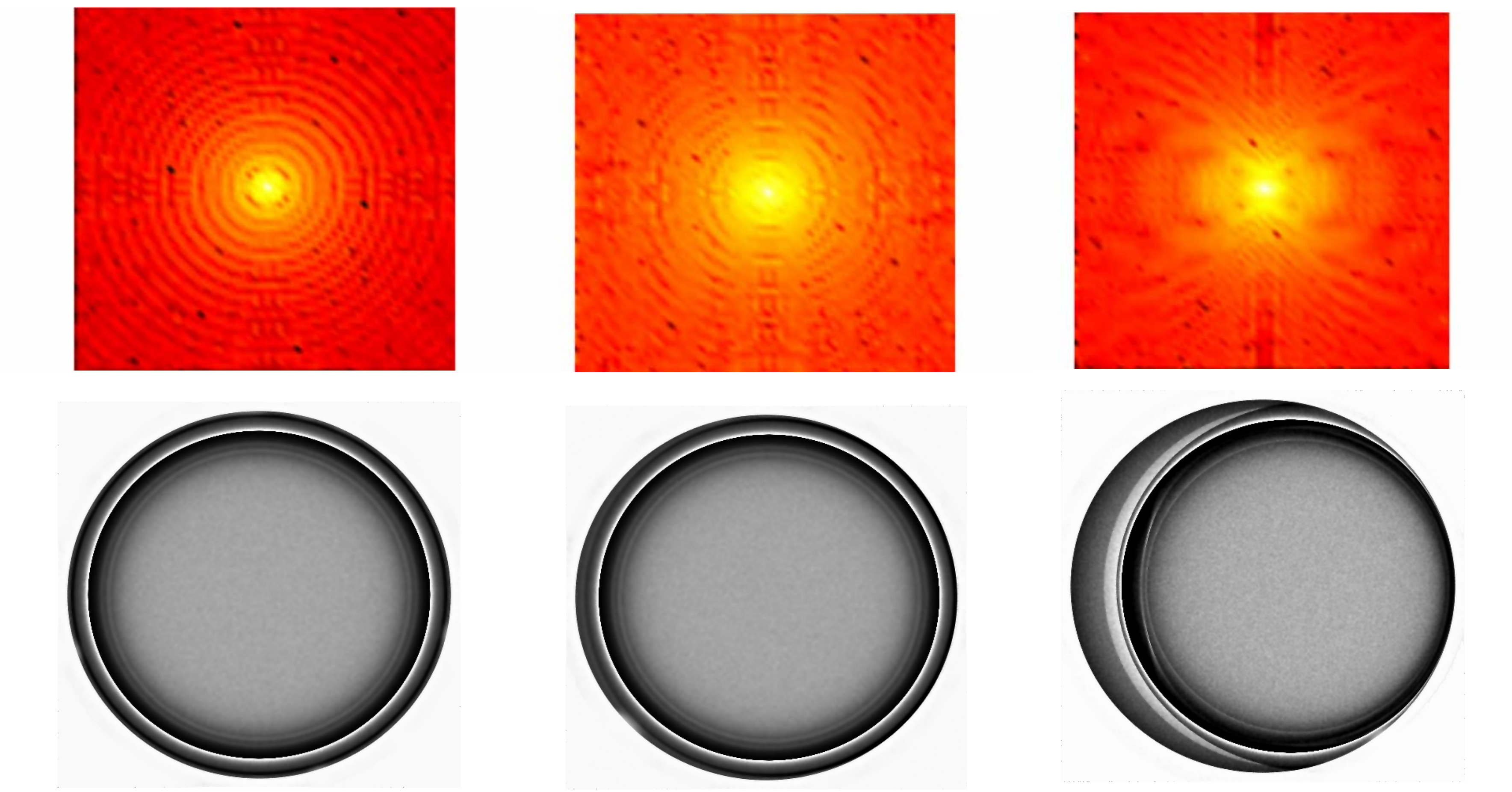
We studied real and synthesized images of shells and cryogenic targets. Considering them as amplitude transparencies we performed two-dimensional numerical Fourier transformation.



Fourier transforms of the images of real shells of different quality

Fourier transforms of the simulated images of cryogenic targets

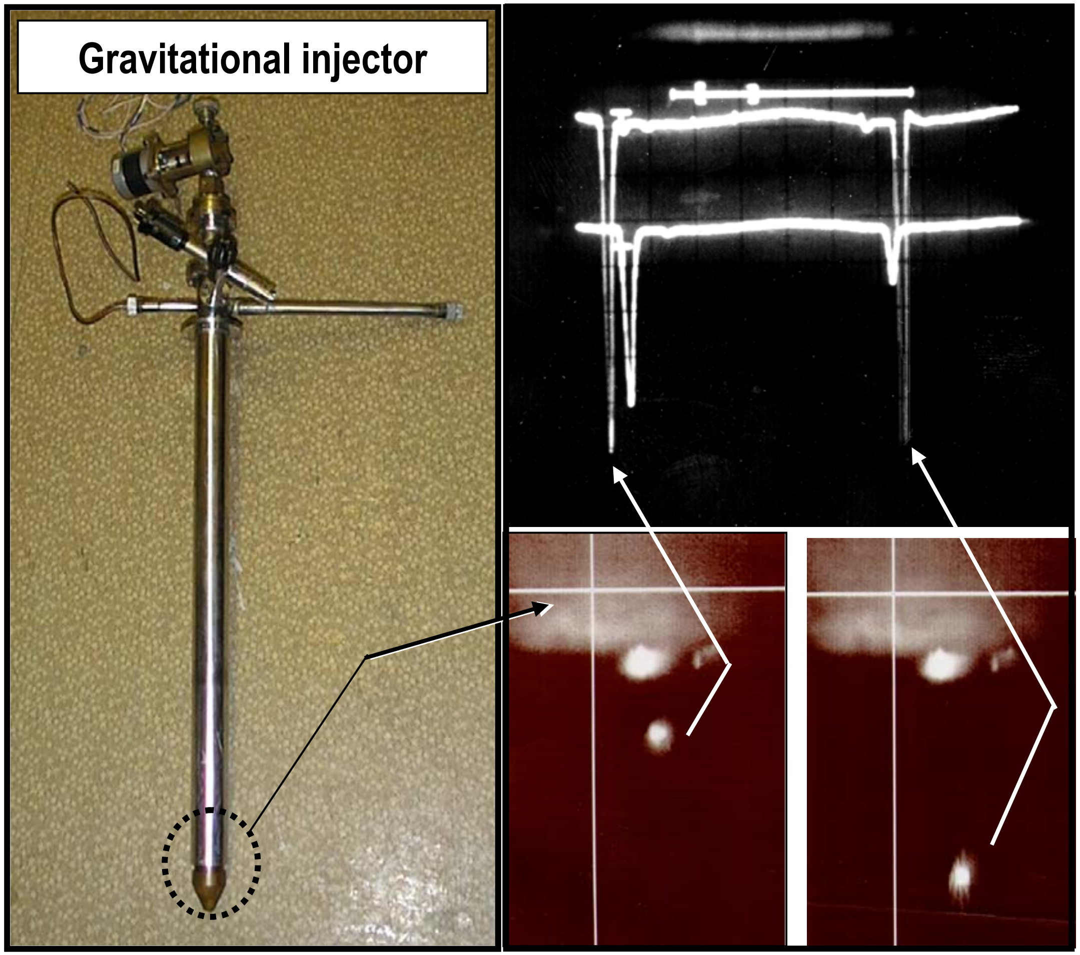
Simulation code *SHELL OPTICS MODEL* developed at LPI has been used. Parameters of simulations: R_1=0.95, R_2=0.8, n_1=1.5, n_2=1.14, A=60° (R1 and R2 are normalized to outer target radius)



Δx/R=0 **Δx/R=1.5%** **Δx/R=14.9%**

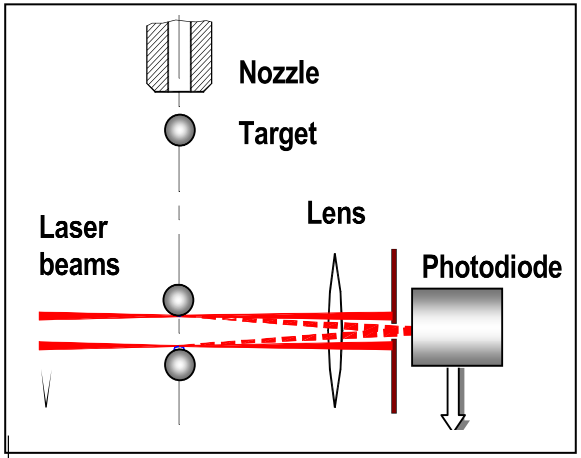
Target flight monitoring.

Gravitational injector and electro-optical scheme have been created at LPI and tested under the team work between LPI and RAL (UK)



RESUME ON TARGET FLIGHT MONITORING

1. Target parameters: Glass shell OD=560 μm, ΔR=18 μm
2. Two-beams oscilloscope data
   - Trajectory angular spread: a $\leq$ 3 mrad,
   - Average target velocity: v = 0.55 m/s
3. Fast video recording data (1000 frames/s)
   - Trajectory angular spread: a $\leq$ 3 mrad
   - Average target velocity: v = 0.43 m/s



CONCLUSION

We have developed the scientific, engineering and technology base which is necessary and sufficient to proceed the creation of a prototypical target factory. The project milestones are the following:

Creation of Block II
(IFE targets preparation)

1. Theoretical Modeling
2. Constructing & Modernization
3. Experiments & Testing

- Operation in a single step mode
- Operation in a rep-rate mode

Modernization of Block I
(Shells preparation)

1. Required minimal modernization
2. Main problem: CH shells of ∅ 4 mm fabrication

Creation of Block III
(acceleration & in-flight characterization)

1. Theoretical Modeling
2. Constructing & Modernization
3. Experiments & Testing

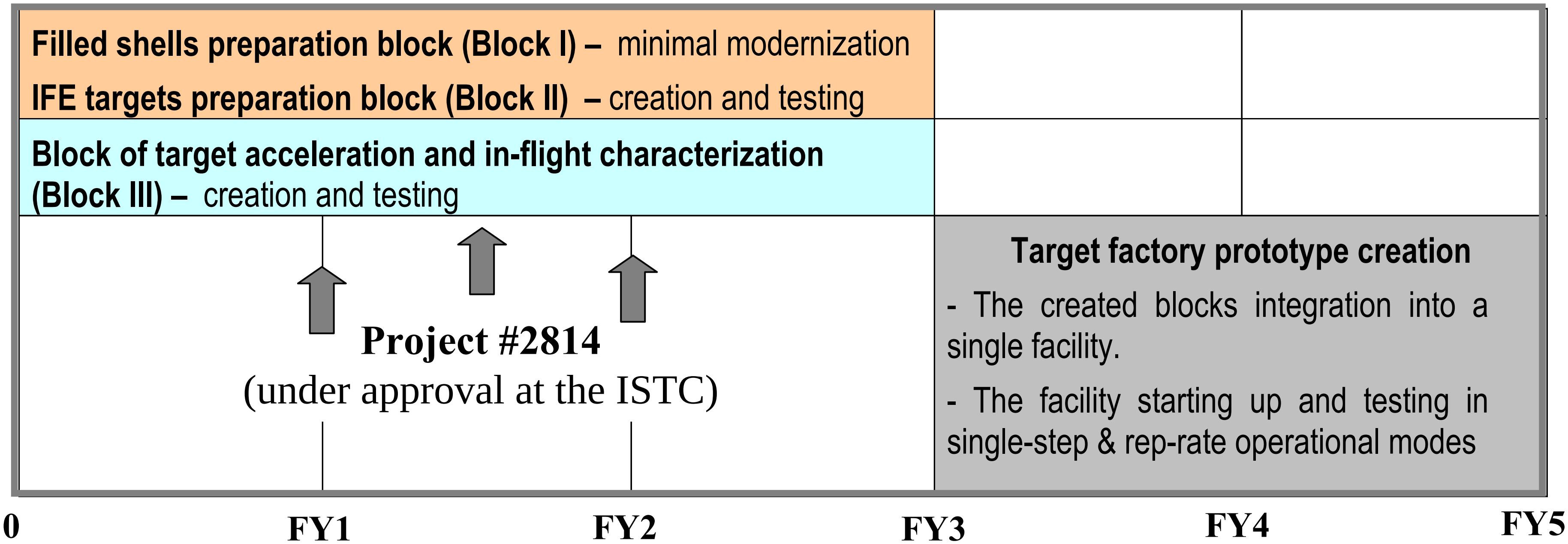
- Operation in a single step mode
- Operation in a rep-rate mode

Target factory prototype creation

1. All units integration
2. Facility setting up and testing

- Operation in a single step mode
- Operation in a rep-rate mode

Our goal to have the facility ready in 5 years



It is proposed that the tasks of creating the Blocks I & II and Block III shall be resolved in parallel. This will allow the time necessary for development and commissioning of the facility in full configuration to be reduced by 3 years.

The facility creation will allow to demonstrate the repeatable IFE target fabrication and injection based on the FST technologies.

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10. B.V.Kuteev. *Interaction of Cover and Target with Xenon Gas in the IFE-Reaction Chamber*. Nov. 2001, Research Report NIFS-718, National Institute for Fusion Science (Japan)