Cryogenic Target Group

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High rep-rate fabrication, characterization & delivery of free-standing moving cryogenic targets: overview on researches developed at LPI

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TARGET SUPPLY SYSTEM IS ONE OF THE BUILDING BLOCKS OF IFE REACTOR.

OPERATIONAL PRINCIPLE IS THE FST-PRINCIPLE:

HIGH REP RATE OPERATION WITH FREE-STANDING TARGETS

Over the last 20 years, the technologies to operate with free-standing targets at each production step (fuel filling, cryogenic layering, finished target characterization and injection) are under development in LPI

COLLABORATING INSTITUTIONS IN RUSSIA

- *P.N.Lebedev Physical Institute (LPI) is the leading organization
- *A.A.Dorodnitsin Computing Center
- Red Star State Unitary Enterprise
- M.V.Lomonosov Moscow State University
- State Polytechnical University of St.Petersburg

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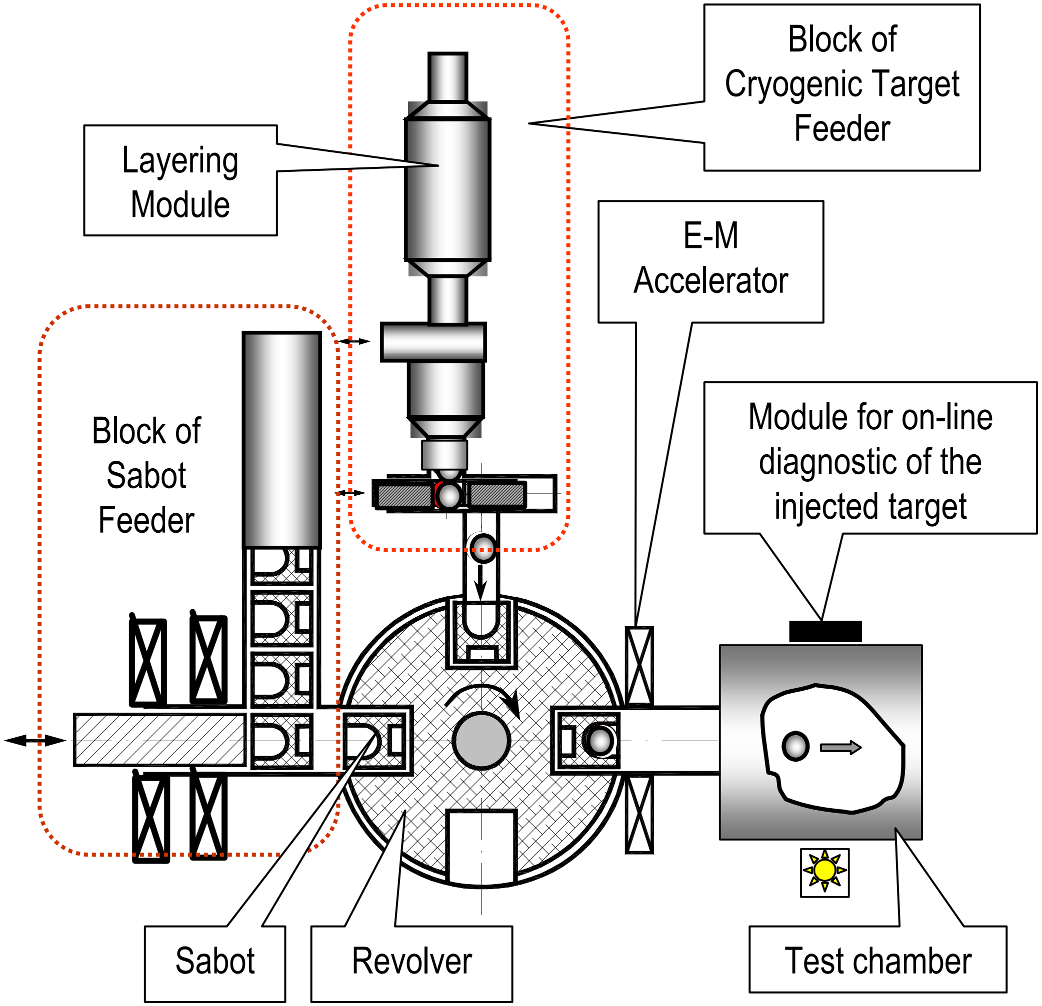
*Russian Academy of Sciences

TARGET SUPPLY SYSTEM BASED ON THE FST-PRINCIPLE

[Osipov et al. IFSA, 2001; LPI & IAEA RC #11536 (2001-2005)]



Block of Cryogenic Target Feeder

Layering Module

E-M Accelerator

Block of Sabot Feeder

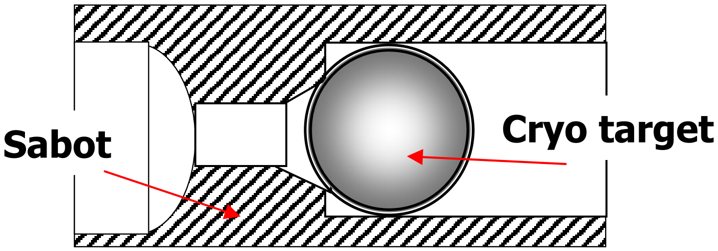
Module for on-line diagnostic of the injected target

Sabot

Revolver

Test chamber

The system uses target & sabot electromagnetic acceleration



Sabot

Cryo target

ASSEMBLY TO BE ACCELERATED

SABOT works as a driving body for cryogenic target. It is also protects the target from heat- and g-loads at the acceleration stage.

❑ THE SYSTEM IS CAPABLE OF

- **Mass-producing the reactor-scaled free-standing cryogenic targets**
- **Repeatable assembly of the target & sabot**
- **Target & sabot acceleration**
- **Target injection and on-line diagnostics**

FST-PRINCIPLE CAN BE USED FOR SPHERICAL DIRECT-DRIVE AND HOHLRAUM OR CYLINDRICAL CRYOGENIC TARGETS. WE DEVELOP A HIGH REP-RATE TARGET SUPPLY SYSTEM IN DIFFERENT PROJECTS.

❑ **REACTOR-SCALED SPHERICAL TARGETS -**
contract #11536 between LPI & IAEA (2001-2005). *The project goal is the extension of the FST technology on IFE requirements.*
- ISTC Project #2814 (approved by the ISTC Governing Board in 2004). *The project goal is creating a prototype of target supply system based on the FST-principle.*

❑ **HIGH GAIN SPHERICAL TARGETS -**
contract between Russian Federal Nuclear Center & LPI (2004-2006). *The project goal is design and feasibility study on FST-based target system to supply of the experiments on 300÷500 kJ multi-beam laser facility*

❑ **CYLINDRICAL CRYOGENIC TARGETS -**
contract between LPI, GSI & HEDgeHOB collaboration (June 2007-March 2008). *The project goal is design and feasibility study on rep-rate fabrication and manipulation of HEDgeHOB cryogenic targets.*

❑ **We propose to develop the FST-based target supply system for HiPER project**

Assurance of success in the projects execution is based on the extensive experience of Cryogenic Target group from LPI in free-standing cryogenic targets fabrication, characterization and delivery.

KEY RESULTS ACHIEVED IN SUPPORT OF THE BUILDING THE TARGET SUPPLY SYSTEM BASED ON THE FST-PRINCIPLE

- **FST-layering.** Free-standing target (FST) technique for a high rep-rate cryogenic layering inside moving free-standing shells has been developed.
- **Demonstration of the main steps of IFE targets supply on a small scale.**
  Demonstration has been realized for CH shells of 1.0÷1.8 mm-diam using the FST-based system created at LPI:

A batch of CH shells (5-to-25) diffusion filling with D2-fuel	**P_f = 100÷1000 atm at 300K** **fill time ≤ 17÷20 hrs**
FST-layering inside moving free-standing shells	**20÷100 µm-thick layer** **layering time ≤ 15 sec**
Injecting the cryogenic targets into the test chamber	**0.1 Hz rep-rate**

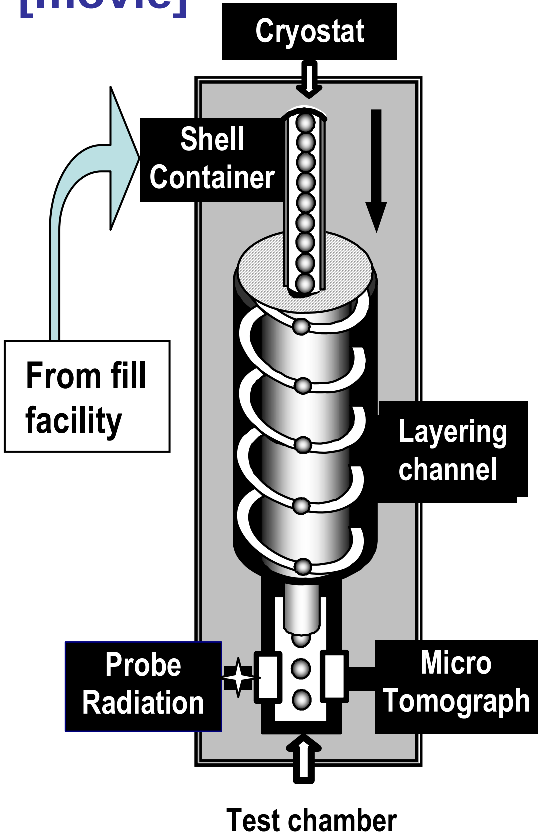
- **Target characterization**

  Finished target precise control. A 100-projections visual-light micro-tomograph has been created and tested: spatial resolution is 1 µm for 490 nm probe radiation.

  Injected target on-line diagnostics. Optical scheme based on Fourier holography has been proposed for on-line diagnostics of the injected target. The scheme operability has been proved in a number of the computer experiments. Operational rate of the scheme is of several µsec
- **Target survival study.** Fuel layer must be in an ultra fine state, which brings minimal risk of fuel layer destruction due to the heat- and g-loads. The ultra fine D2-layer has been formed by the FST technique in presence of a high melting additive.
- **Delivery.** The coil gun have been created and successfully used in the experiments on ferromagnetic sabot acceleration at cryogenic temperatures (4.2K & 77K). Magneto-insulators has been defined as optimal sabot material.

MAIN PRINCIPLES OF THE FST LAYERING MODULE OPERATION

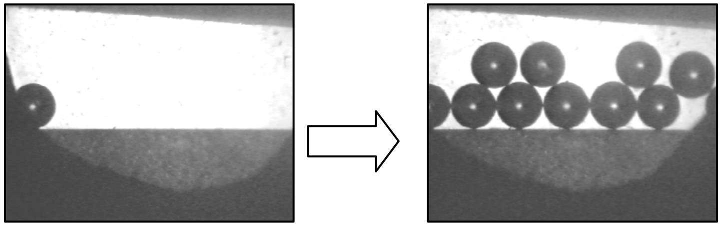
[movie]



FST layering module with a spiral layering channel

For achieving successful layering results, proper allowance must be made for the following:

- targets must be free-standing, and must move in the layering channel
- uniform layer formation is based on liquid fuel symmetrization due to random target rotation during its spiral rolling in the layering module
- fuel freezing based on conduction cooling of a batch of moving spherical targets
- transport process is target injection between shell container – layering module – test chamber

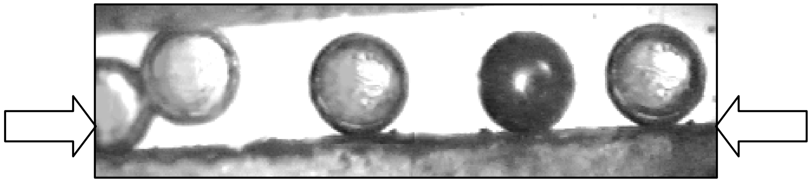


t = 0

t = 100 sec

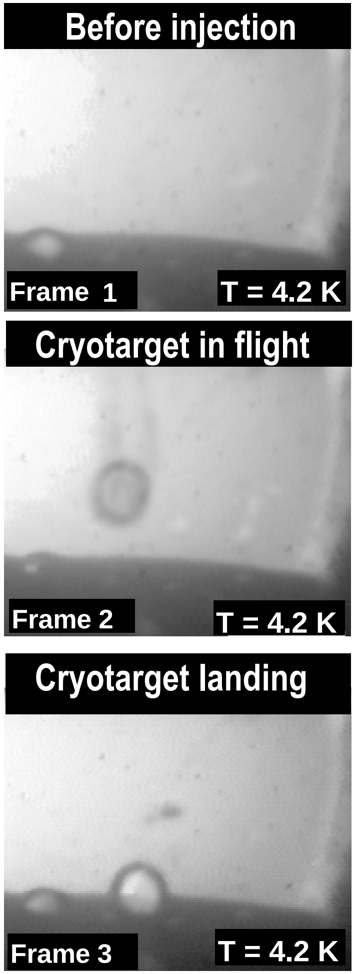
Repeated target injection from the layering channel to the test chamber at 4.2 K: f = 0.1 Hz

Results of the FST layering for a batch of CH shells ∅ 0.9-1.0 mm; f = 0.1 Hz

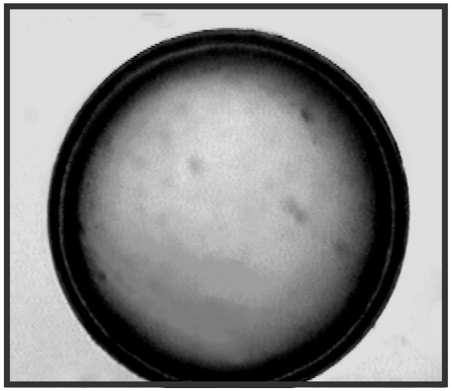


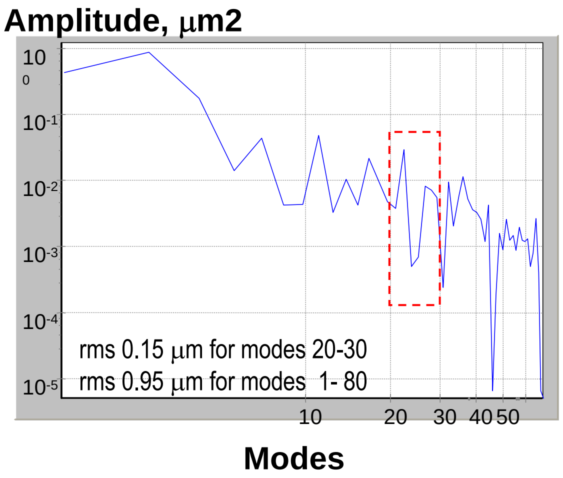
Solid H_2–layer W=87-90 µm

CURRENT EXPERIMENTAL RESULTS ON THE FST LAYERING:
CH shell ∅≤1.5 mm, W=20÷50 μm, layering time <15 sec



Cryogenic target injection into the test-chamber at T= 4.2 K





Cryogenic layer consists of the D_2/Ne mixture.

Here Ne modeling the behavior of heavy component (tritium) in DT mixture.

CH shell of ∅ 1230 μm, 41 μm thick cryolayer from 80%D_2+20%Ne.

Fourier spectrum results: rms 0.15 μm for modes 20-30.

FST method holds much promise for the thermal-stable ultra-fine cryogenic layer formation from DT-mixture

PRECISE CHARACTERIZATION OF CRYOGENIC TARGET USING A 100-PROJECTIONS VISUAL-LIGHT MICROTOMOGRAPH CREATED AT LPI

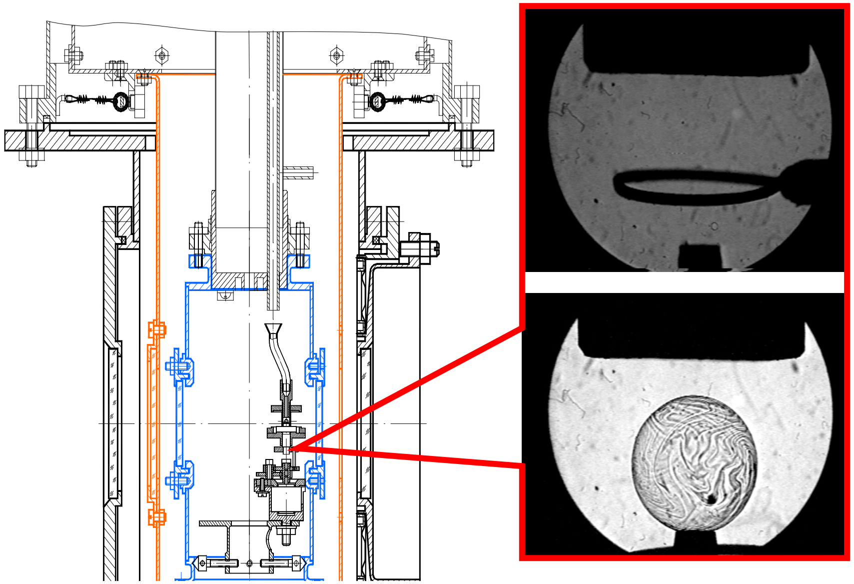
[DEVELOPED UNDER THE ISTC PROJECT #1557]

☐ Cryogenic target transport under gravity from the layering channel to a drive shaft of target positioning device

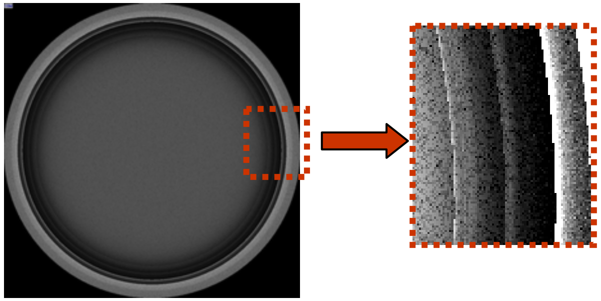
☐ Conditions for cryogenic target scanning:
- Cryostat and radiation source are fixed
- Target rotation around vertical axis
- Minimal rotation angle 1.3^0, full angle 360^0
- Probe radiation of 490 nm wave length
- Number of projections: 30 -to- 100
- Spatial resolution is 1 μm

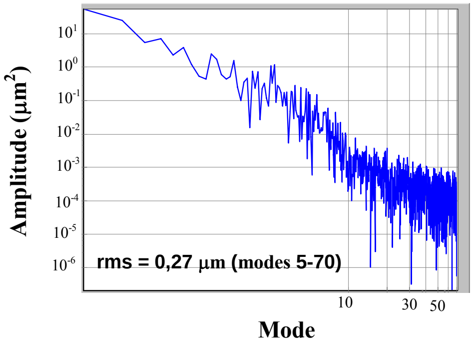
☐ Projection data processing using a special developed software package *Target Studio*

☐ Reconstruction algorithm is based on the analysis of the bright band position on target shadow image.

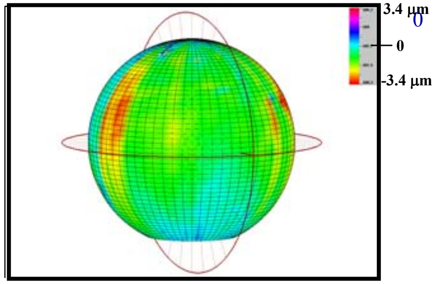


Target positioning device is placed inside the tomographic test chamber of cryostat





Fourier spectrum of the bright band RMS=0.27 μm (modes 5-70)

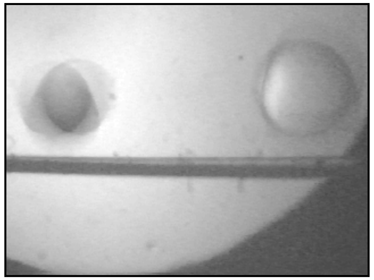


CH shell inner surface: reconstructed using 90 shadow images

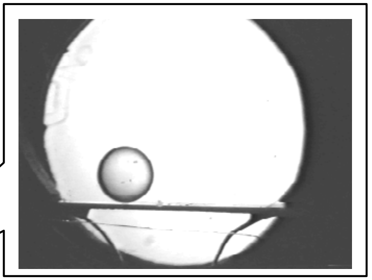
FOR EXPERIMENTS WITH IFE TARGETS WE CONSIDER NEW DESIGN OF THE FST-LAYERING MODULE: A SPECIAL ROTATING AND BOUNCING (R&B) CELL

[E.R.Koresheva et al., Proc.29th ECLIM, July 2006, pp.551-561; Fus.Sci.Tech 2003]

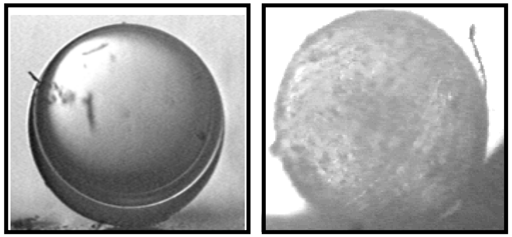
The R&B cell is mounted at the bottom of the layering module. The couple "membrane & target" is driven by an input signal generated due to inverse piezoelectric effect. Device has been tested at the 4.2÷77 K and 300 K. Generated movement modes: target rotation (R), reflection from the crystal surface (B) or mixed mode (R&B)



B mode at 4.2 K



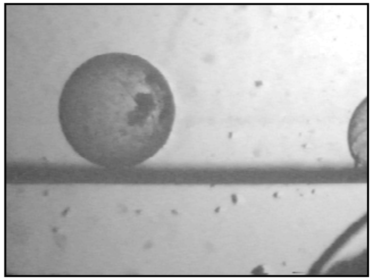
B mode at 77 K



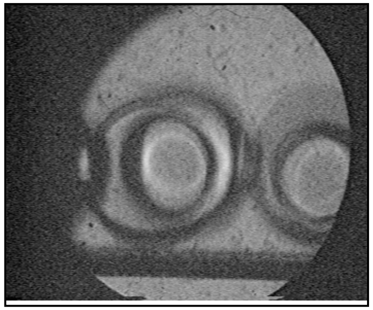
(a) (b)

Cryogenic D2-layering using the R&B cell:

(a) 20K - before layering,
(b) 5.8 K - after layering;
1.2 mm-diam. CH shell; D2 layer 47-μm-thick; formation time: <60 s
Piezo-crystal - 10 kHz, 75V



R mode at 6 K

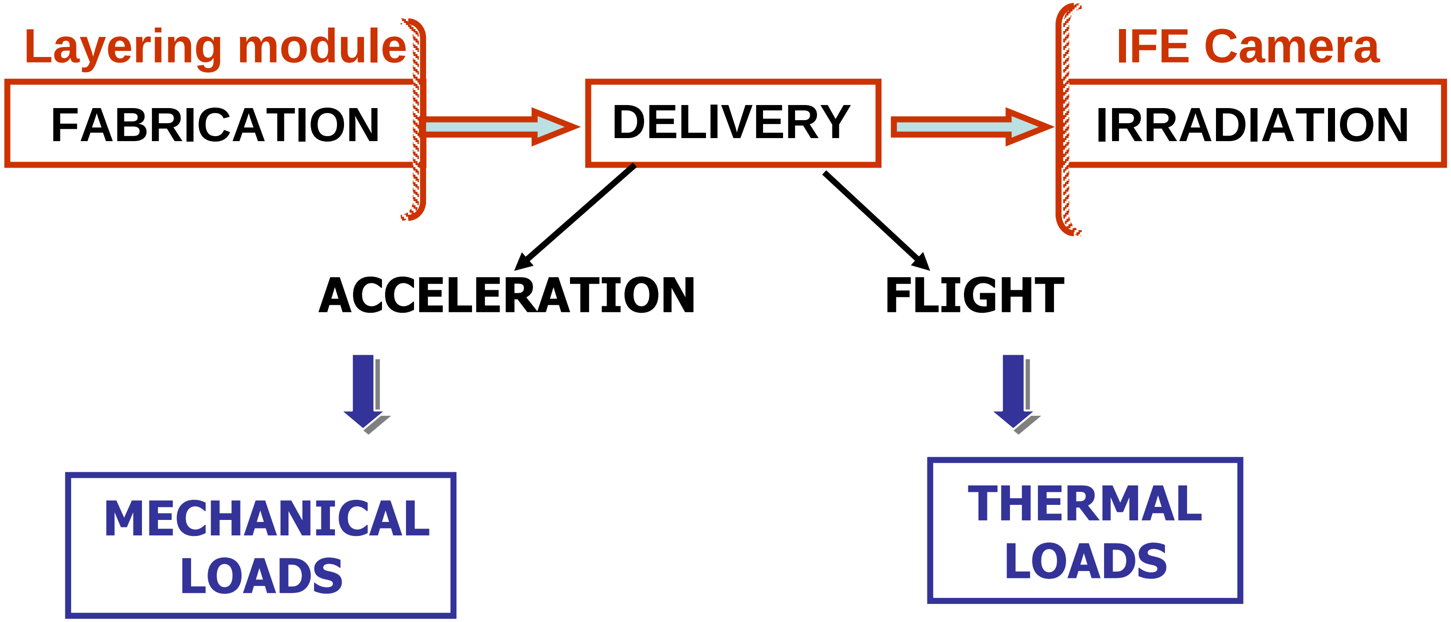


R&B mode at 300 K

In the R&B cell the layer simmetrization & freezing take place in a very small area as compared to the layering channel

Possible problem: CH capsules adhesion.
Application of e - source is advisable

TARGET SURVIVAL DURING ITS DELIVERY



Layering module

FABRICATION

DELIVERY

IFE Camera

IRRADIATION

ACCELERATION

FLIGHT

MECHANICAL LOADS

THERMAL LOADS

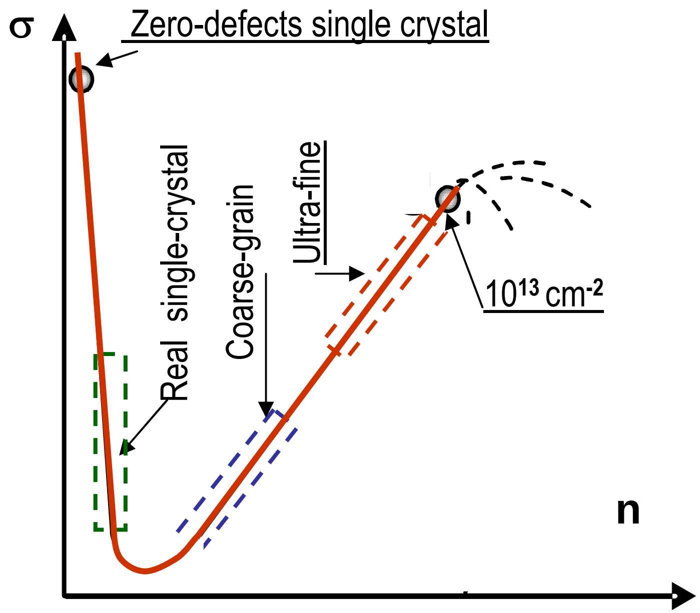
Problem under consideration:
Mechanical damage of target components

Problem under consideration:
Fuel layer distortion in high & low modes

Research of the target survival issues with a special attention to the fuel layers with inherent survival features

TARGET ACCELERATION: the strength analysis has shown that the ultra-fine fuel layer can withstand to much more overloads than crystalline layer

Zero-moment theory of S.P.Timoshenko → **$a/g \sim \sigma/\rho$** → **σ/ρ is maximal for ultra-fine layers**



Sample strength (σ) vs. defect density (n)

STRENGTH ANALYSIS RESULTS

- **The main parameter, which defines the value of permissible over loads is the ratio σ/ρ**
- **The more the parameter σ/ρ , the more permissible overloads a/g**
- **Hall-Petch relation** (valid for grain size $d \geq 10$ nm; σ_m is the fluidity limit of the material)**:**

$$\sigma_m \sim d^{-1/2}$$

- **The density of ultra-fine materials is no more then that of coarse-grained counterparts**

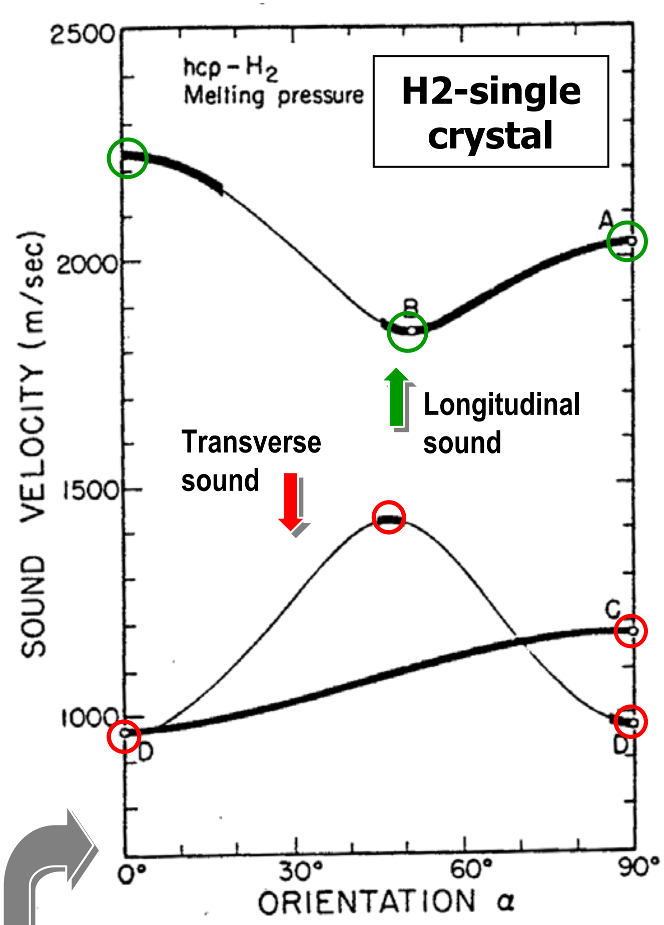
RESUME: THE RATIO σ/ρ IS MAXIMAL FOR ULTRA-FINE LAYERS

TARGET FLIGHT INSIDE REACTION CHAMBER, UNIFORM HEAT FLUX.

Fuel layer degradation under the thermal loads depends on the layer anisotropy

1. In its equilibrium solid hydrogen is hexagonal molecular crystal.
2. In hexagonal crystals the sound speed depends on sound wave line about the crystallographic axes. The difference in sound velocity ***v*** for single H2- and D2- crystal makes up to **~ 19%** [R.Wanner, Phys.Lett. 1972; J. Law Temp. Phys. 1973]
2. In molecular crystals the mechanism of heat conduction is mainly connected with lattice conductivity, which depends on sound speed (Debye`s theory): $k \sim (1/3)C\Lambda v$

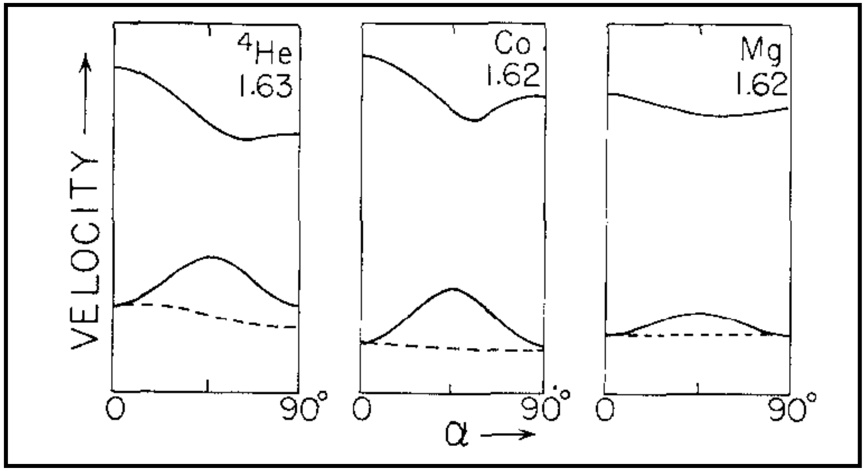
RESUME: Even under condition of uniform heat flux, the inner surface of anisotropic fuel layer may loose its smoothness



H2-single crystal

Longitudinal sound

Transverse sound



Direction dependence of sound velocity in hexagonal crystals: hcp-H2 (Fig. above), and ^{4}He, Co, Mg (Fig. on the left)

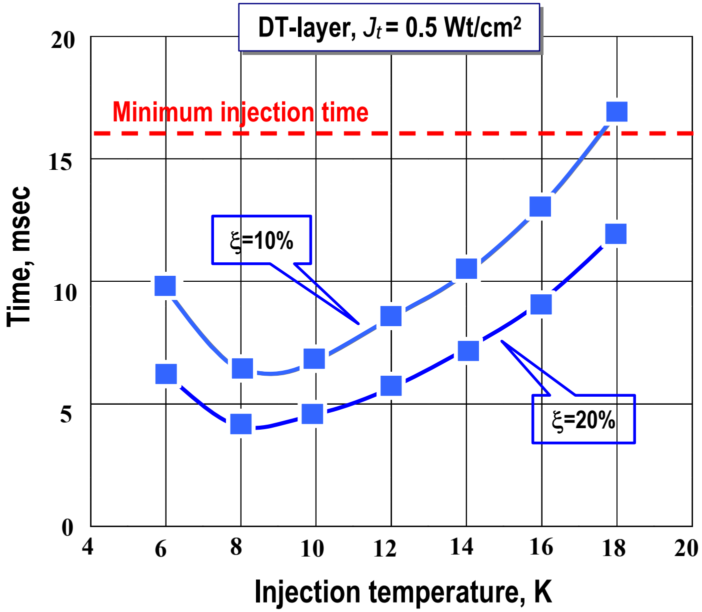
CALCULATION SHOWS (for uniform heat flux)**: Anisotropic fuel layer degrades before the moment of target arrival at the chamber center.**

APPLICATION OF ULTRA-FINE FUEL LAYER ALLOWS TO SOLVE THE PROBLEM.

Time for surface roughness growth , msec

ξ, %	Target injection temperature Ti = 10 K			
	J_t= 5 Wt/cm^2		J_t= 0.5 Wt/cm^2	
	D2	DT	D2	DT
3	6.4	5.4	15.4	13
5	4.7	4	11.5	9.7
10	3	2.6	7.6	6.5
15	2.4	2	6.1	5.1
20	2	1.7	5.1	4.4

The minimum time of target delivery at the chamber center ~ 16 ms



Time of surface roughness growth from 0 up to 0.5 μm *vs* layer anisotropy ξ for a range of injection temperature T_i

AN APPROACH BASED ON STEPHEN'S PROBLEM for singularly perturbed simultaneous equations of thermal conductivity with semi-linear boundary and initial conditions is used to model the process of anisotropic fuel layers degrading

DATA FOR CALCULATION:

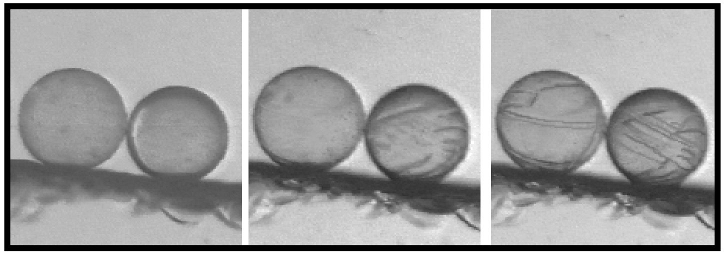
- Classical high gain target: CH shell of 4-mm diam., 45-μm thick wall, 200 μm thick DT-layer
- Radiated heat load (close to SOMBRERO chamber): uniform heat flux 56 W/cm^2 Chamber wall T=1758 K
- At the chamber center, the DT-ice layer must be at T = 18.5 K

DATA FOR INJECTION:

- Chamber radius: 6.5 m
- Injection velocity: ~ 400 m/sec (near the maximum practical velocity)
- The minimum time of the target delivery at the chamber center ~ 16 msec.

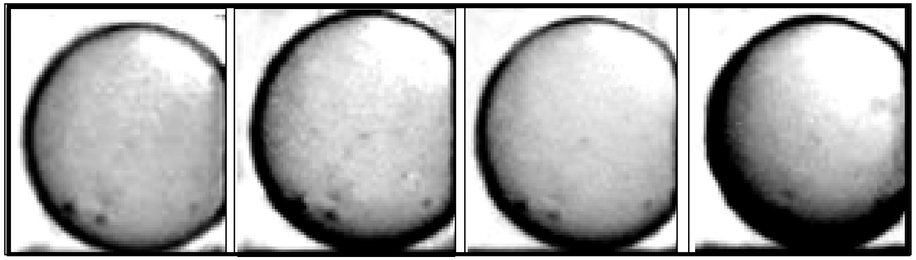
FST METHOD: FORMATION OF A THERMAL-STABLE ULTRA-FINE LAYER REQUIRES TO USE A HIGH-MELTING DOPING (ADDITIVE) TO A FUEL

H2-layer; no additives



Transparent solid H2-layer re-crystallization under target heating (T_{tp}=13.96K)

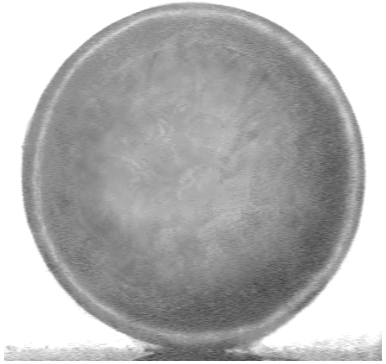
Using HD (5%) as additive to H2 (95%)



Transparent solid cryogenic layer does not re-crystallize in a wide temperature range from 5 K to T_{tp}.

Using 3%Ne as additive to D2 (here Ne modeling the behavior of heavy component (tritium) in DT mixture)

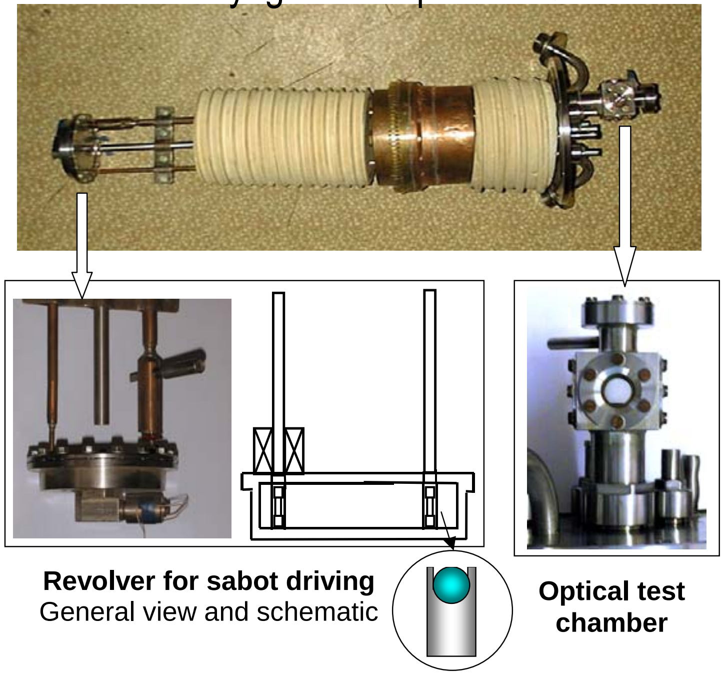
TARGET PARAMETERS	
CH shell ∅ :	**1500 μm**
Shell wall thickness:	**20 μm**
Shell overcoating:	**200 Å Pt/Pd**
Fill pressure (300 K):	**~270 atm**
Fuel gas density (300 K):	**~38 mg/cm³**
Cryogenic layer components:	**97%D_2+3%Ne**
Cryogenic layer thickness:	**50 μm**



EXPERIMENTAL CONDITIONS	
Spiral layering channel: **L=1.5 m**	**ID = 2.6 mm**
Target input T:	**31 K**
Test chamber bottom T:	**5 K**
Rarefaction:	**1 mTorr**
Residence time (layering time upper limit):	**10 sec**
Estimated layering time:	**1.57 sec**
Estimated cooling rate:	**7.9 K/sec**

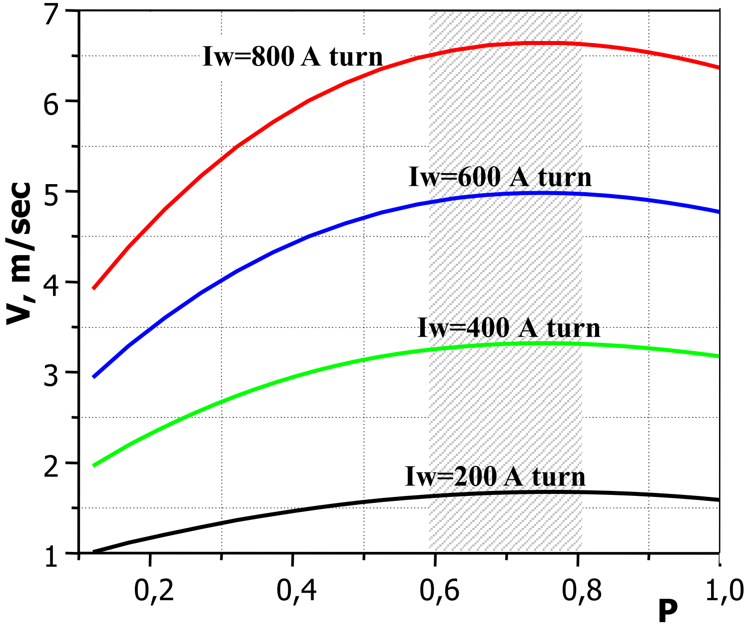
TARGET ACCELERATION: sabot material - research & optimization

Test model of the e.-m. injector working at cryogenic temperatures



Revolver for sabot driving
General view and schematic

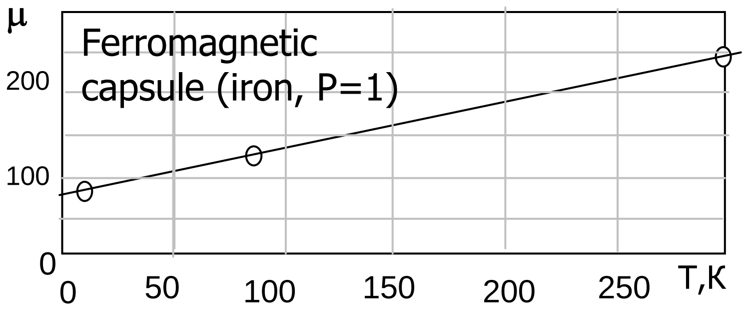
Optical test chamber



Sabot velocity vs. the volume fraction (P) of ferro particles into the polymer matrix of a magneto-dielectric. In optimal case P=0.6-to-0.8

Sabot length is 7 mm, OD is 5.6 mm, density of the material of ferro particles is 6.5 g/cm3, density of polymer matrix (foam polystyrene) is 0.5 g/m3, initial factor of magnetic penetration μ=125. Coil length is 10.5 mm, ID 5.7 mm

- ❑ **CALCULATIONS**: application of a sabot from magneto-insulator makes energy consumption on target acceleration minimal. Optimal: P=0.6-0.8

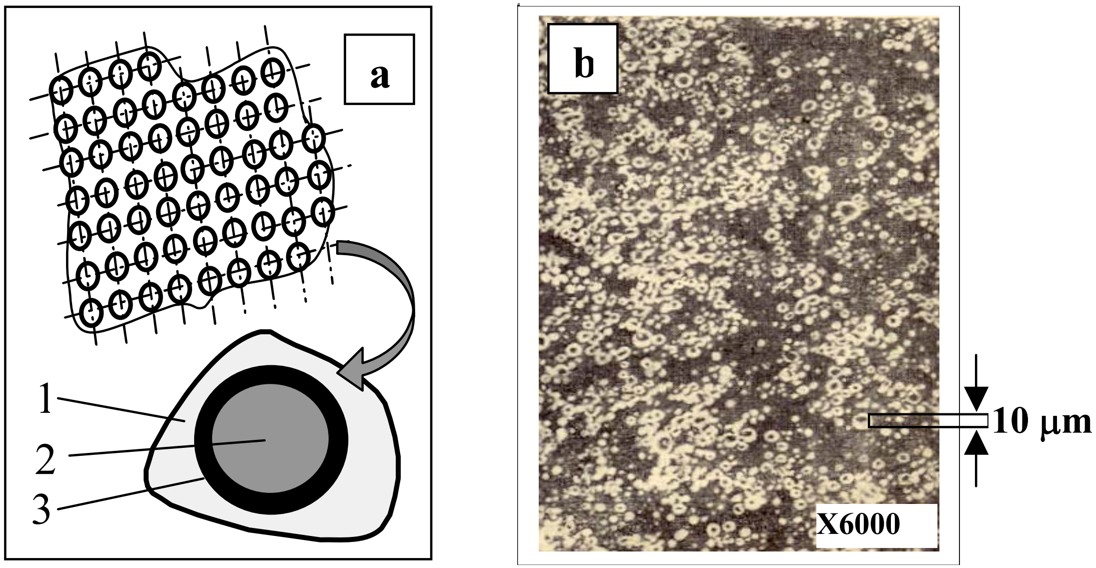


Magnetic penetration factor of the magneto-soft iron *vs.* temperature

- ❑ **EXPERIMENT**: Sabot from magneto-soft iron can be used at work temperatures ≤10-11 K

Magneto-insulator as perspective material for sabot

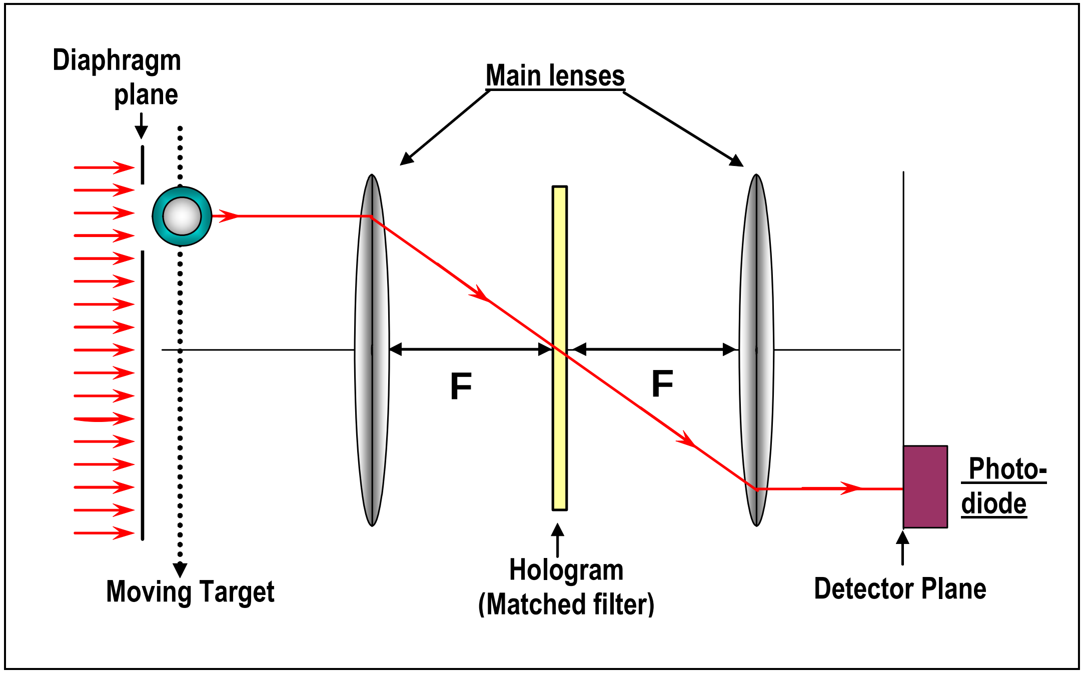
Application of magneto-insulator allows (1) to reduce eddy current, (2) to reduce sabot weight, and (3) to optimize the sabot material interaction with a solenoidal electro-magnetic field.



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

TARGET FLIGHT: Fourier holography of image recognition is proposed for on-line characterization of the injected cryogenic target

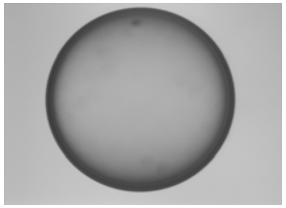
- ☐ Objective performs the Fourier inversion of the product of the Fourier transform of input signal and the Fourier transform of etalon image (i.e. target of ideal quality) recorded in the filter
- ☐ Then the light passes to a photo-sensor (single photo-detector). The recognition signal is greater in the case of better conformity between the real and the etalon images
- ☐ Actuating unit and photo-detector only determine the operation rate of such a scheme, which is ~ several μsec



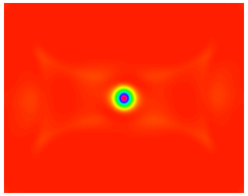
Numerical model has been developed to verify the sensitivity of the considered optical scheme to object recognition. The shadow target images are considered as amplitude transparencies. The model is realized as a complete computer program *Hologram* operating in Windows (2000, XP).

Computer experiments have demonstrated much promise of the Fourier holography approach for on-line diagnostics

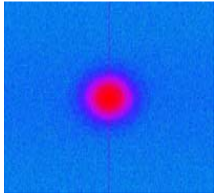
- ☐ Recognition of the target imperfections in both low- and high- harmonics
- ☐ Quality control of both a single target and a target batch
- ☐ Simultaneous control of both an injected target quality, its velocity and trajectory



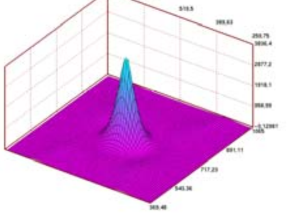
Single shell real image that we used as both etalon and studied object



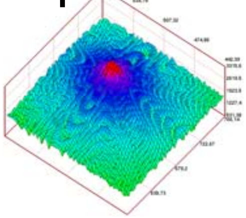
Auto-correlation matrix

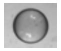


Fourier spectrum

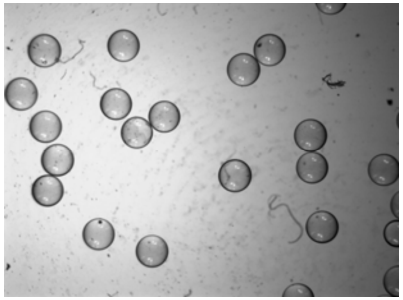


3D

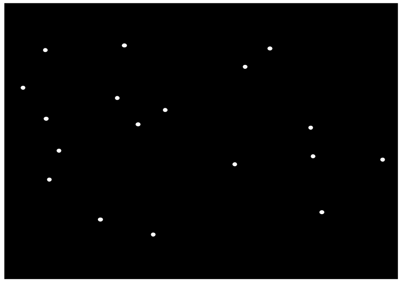




← Etalon image



Studied image of the shells batch

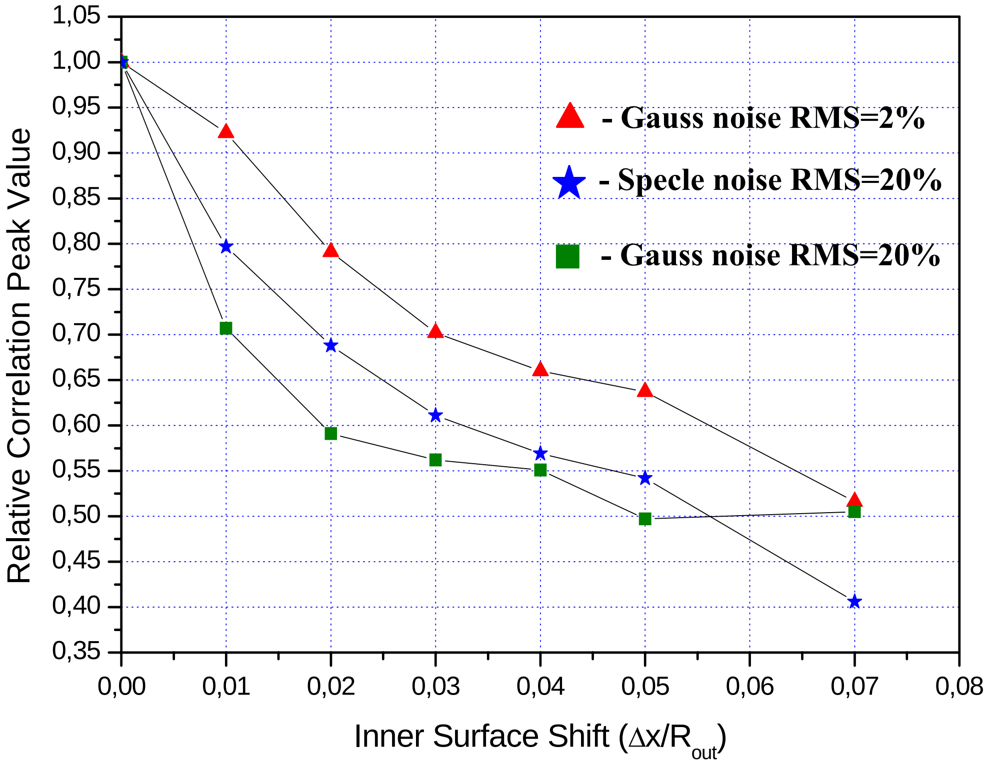


Cross-correlation matrix of the studied and etalon images

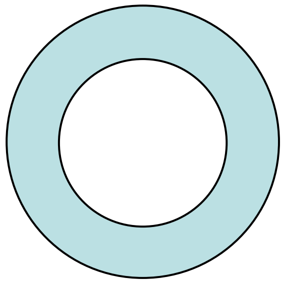
The correlation peak positions (below) corresponds to the shells positions (on the studied image, above)

Investigation of the holographic scheme sensitivity to target shape distortions (1)

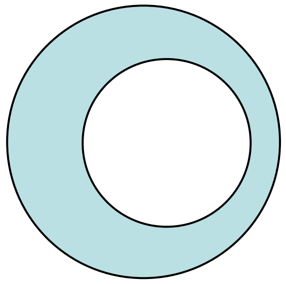
Low-frequency modes recognition (layer non-uniformity)



The relative amplitude of the correlation peak *vs.* inner surface shift (layer non-uniformity)



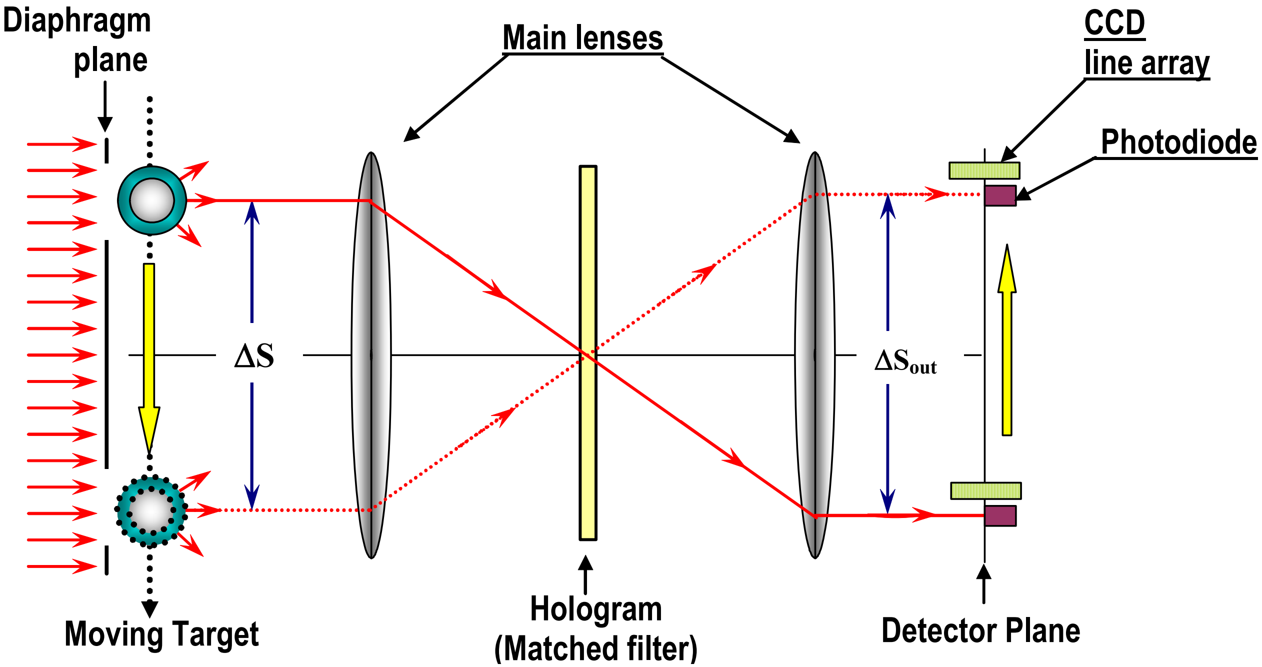
Etalon image



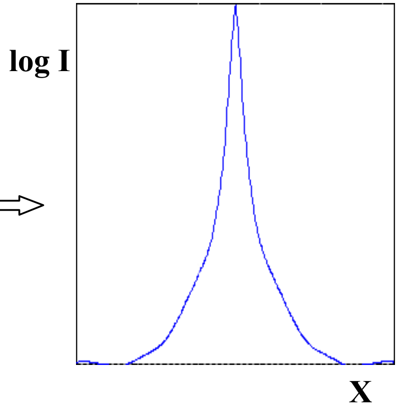
Investigated image

Even at very high noise the tendency of the correlation peak amplitude reducing due to increasing the target asymmetry is evident.

OPTICAL SCHEME FOR SIMULTANEOUS CONTROL OF THE INJECTED TARGET NON-UNIFORMITY AND ROUGHNESS, VELOCITY AND TRAJECTORY



If target shape is close to the shape of etalon target, the correlation peak is very sharp and intensive



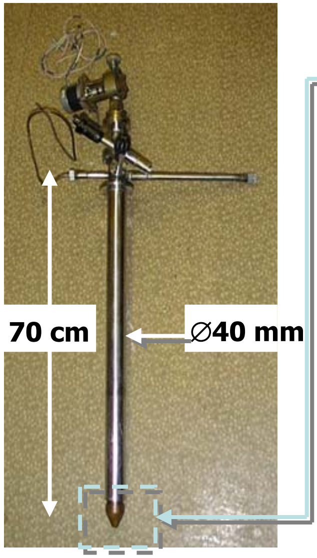
The correlation peak in the detector plane moves in the direction, which is opposite to the direction of target motion

INJECTED TARGET TRACKING BY OPTICAL METHOD HAVE BEEN REALIZED

Observations made in the frame of team work of LPI and Central Laser Facility (UK)

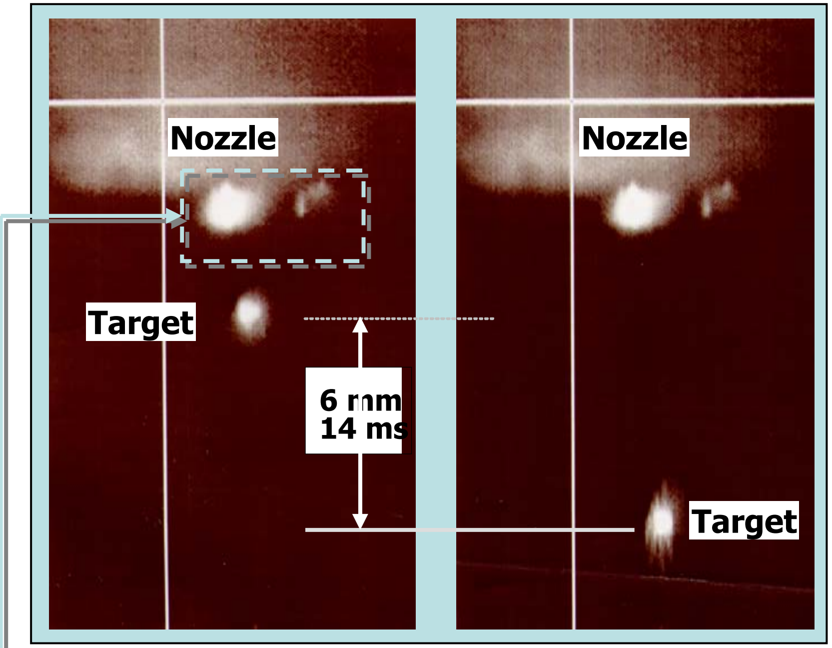
TEST MODEL OF INJECTOR

INCLUDING:
rep-rate target supply system, FST-layering channel, and nozzle



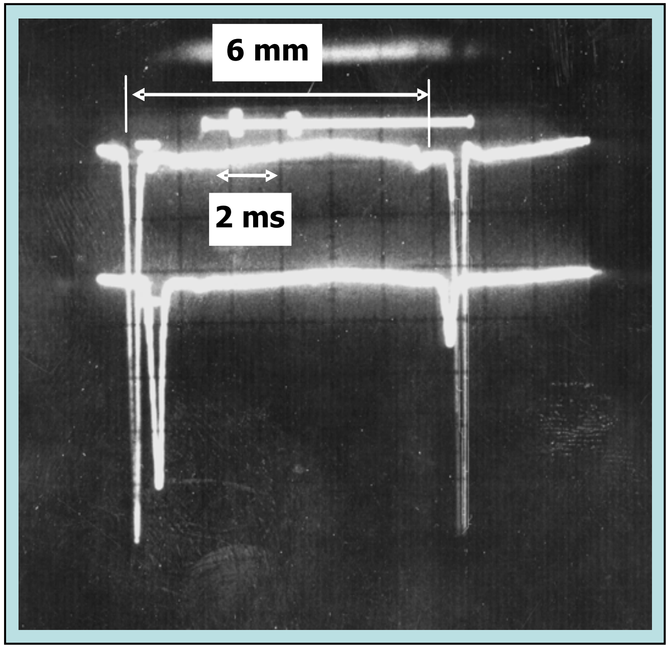
INJECTED TARGET FLIGHT FAST VIDEO RECORDING IN THE SCATTERED LIGHT

by movie camera *KODAK ECTAPRO 1000 IMAGER*



TARGET FLIGHT MONITORING BY 2-BEAMS OSCILLOSCOPE *TEKTRONIK 2220*

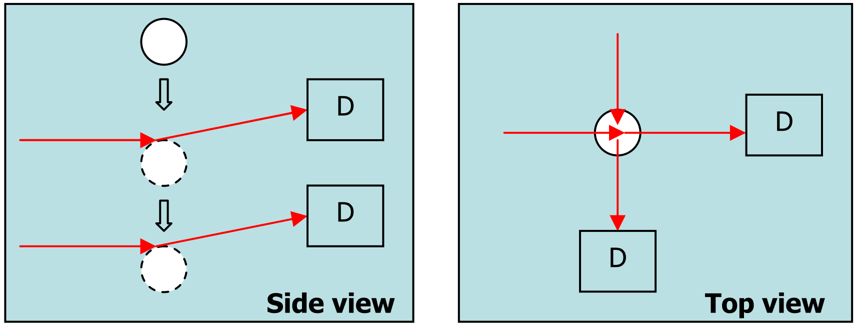
Photo made by *POLAROID C-31*



TARGET FLIGHT MONITORING RESULTS

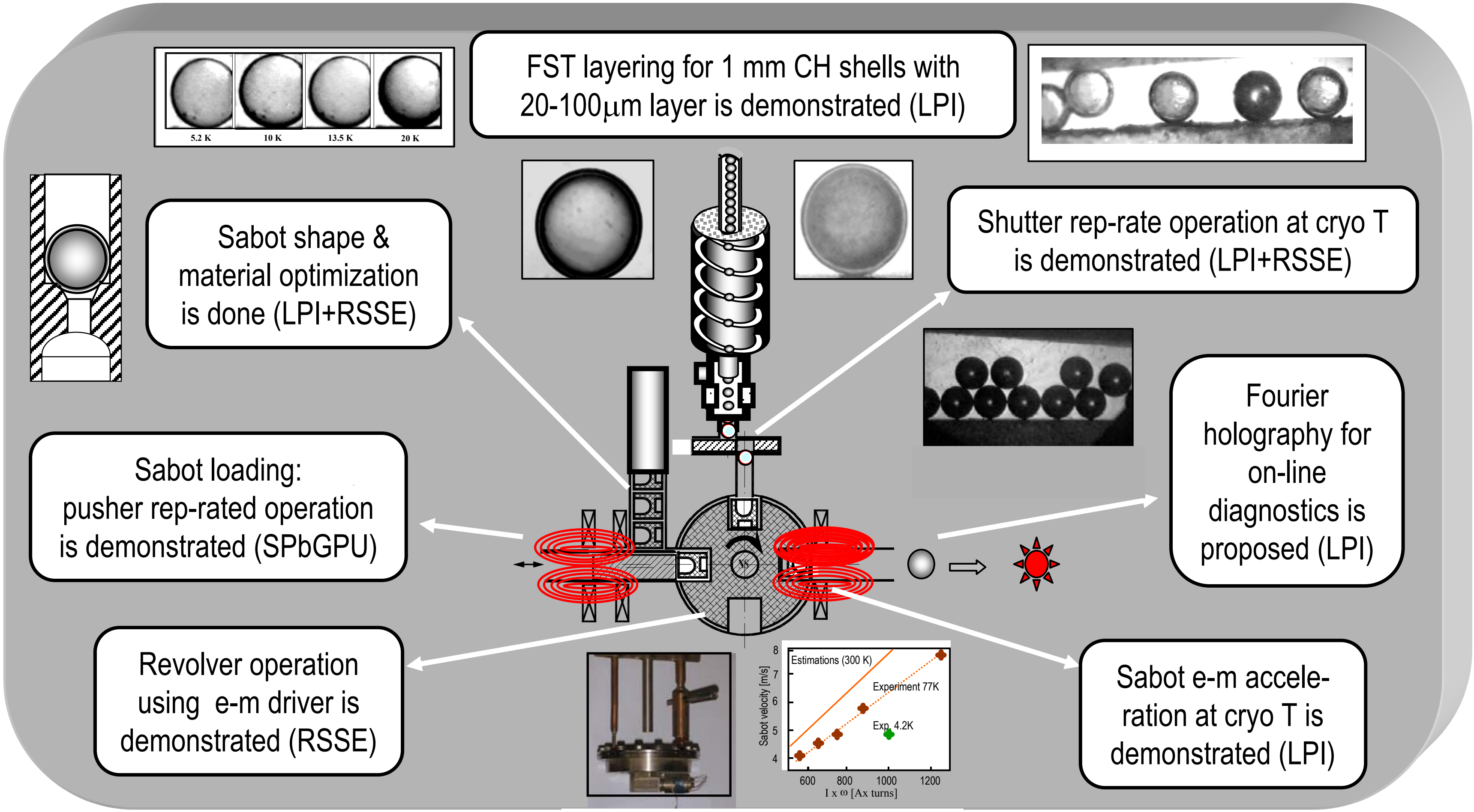
- **trajectory angular spread $\alpha \leq 3$ mrad**
- **average target velocity v = 0.55 m/s**

Small angle scattering method



Side view **Top view**

SUMMARY: for the first time, the target supply system based on the FST-principle was proposed and examined (on a small scale) at LPI



FST layering for 1 mm CH shells with 20-100μm layer is demonstrated (LPI)

Sabot shape & material optimization is done (LPI+RSSE)

Shutter rep-rate operation at cryo T is demonstrated (LPI+RSSE)

Sabot loading: pusher rep-rated operation is demonstrated (SPbGPU)

Fourier holography for on-line diagnostics is proposed (LPI)

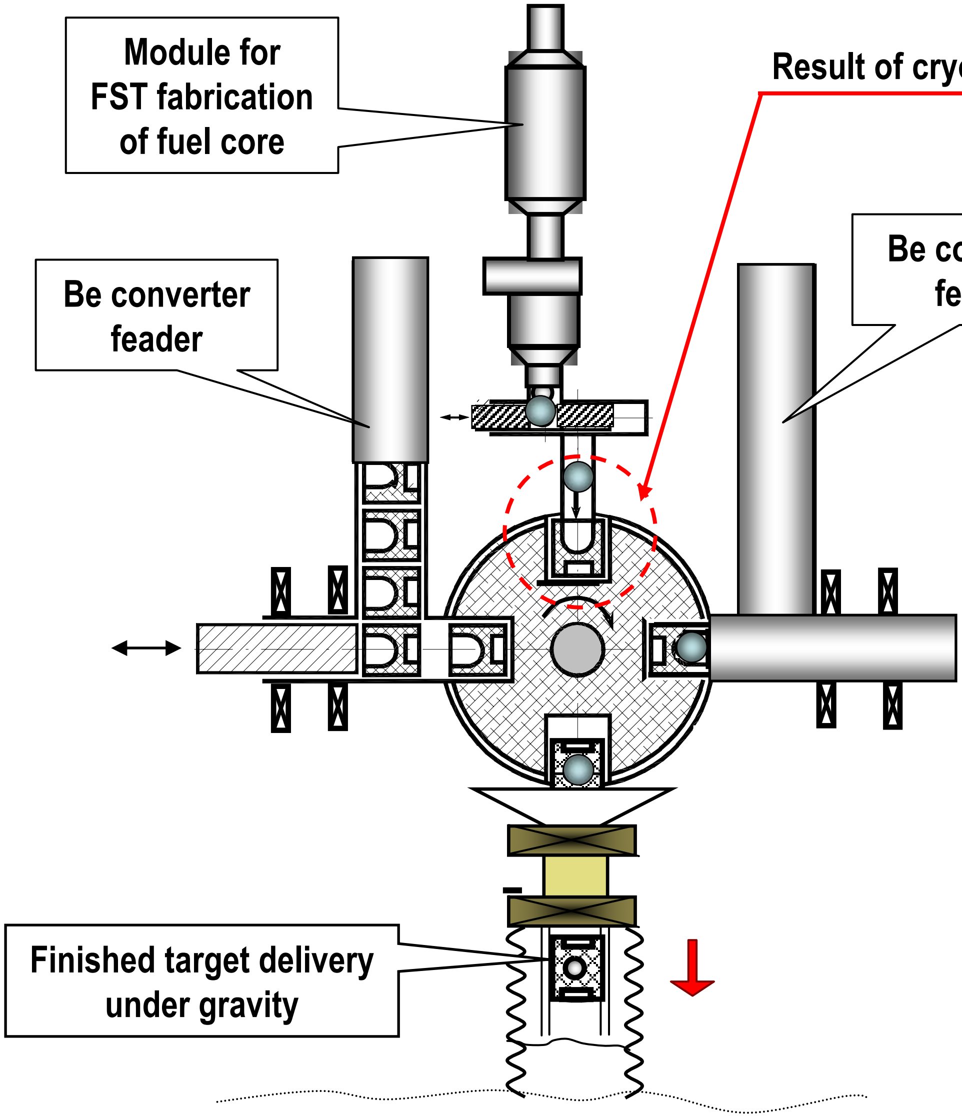
Revolver operation using e-m driver is demonstrated (RSSE)

Sabot e-m acceleration at cryo T is demonstrated (LPI)

Next step is to build the prototype for reactor-scaled targets

THE FST-PRINCIPLE CAN BE USED FOR DIFFERENT CLASS OF TARGETS :

direct-drive, hohlraum or cylindrical cryogenic targets



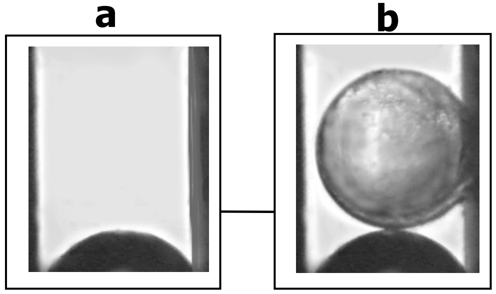
Module for FST fabrication of fuel core

Be converter feader

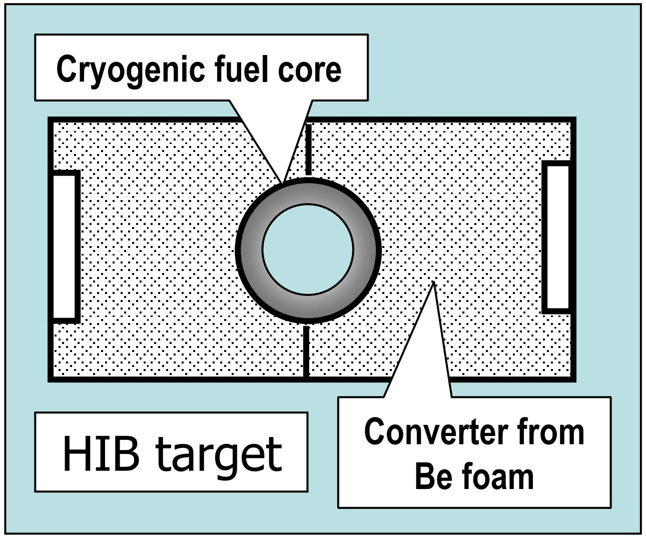
Be converter feader

Result of cryogenic testing

Finished target delivery under gravity



Fuel core injection under gravity inside the cylindrical cavity (5 K):
(a) cavity before injection;
(b) injected target inside the cavity



Cryogenic fuel core

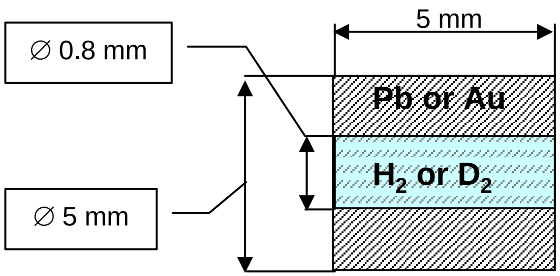
HIB target

Converter from Be foam

TARGET SUPPLY SYSTEM FOR HOHLRAUM TARGETS

TARGET SUPPLY SYSTEM FOR HEDgeHOB CYLINDRICAL CRYOGENIC TARGETS BASED ON THE FST-PRINCIPLE [Report P034, 30th ECLIM]

HEDgeHOB cryogenic targets for LAPLAS experiments



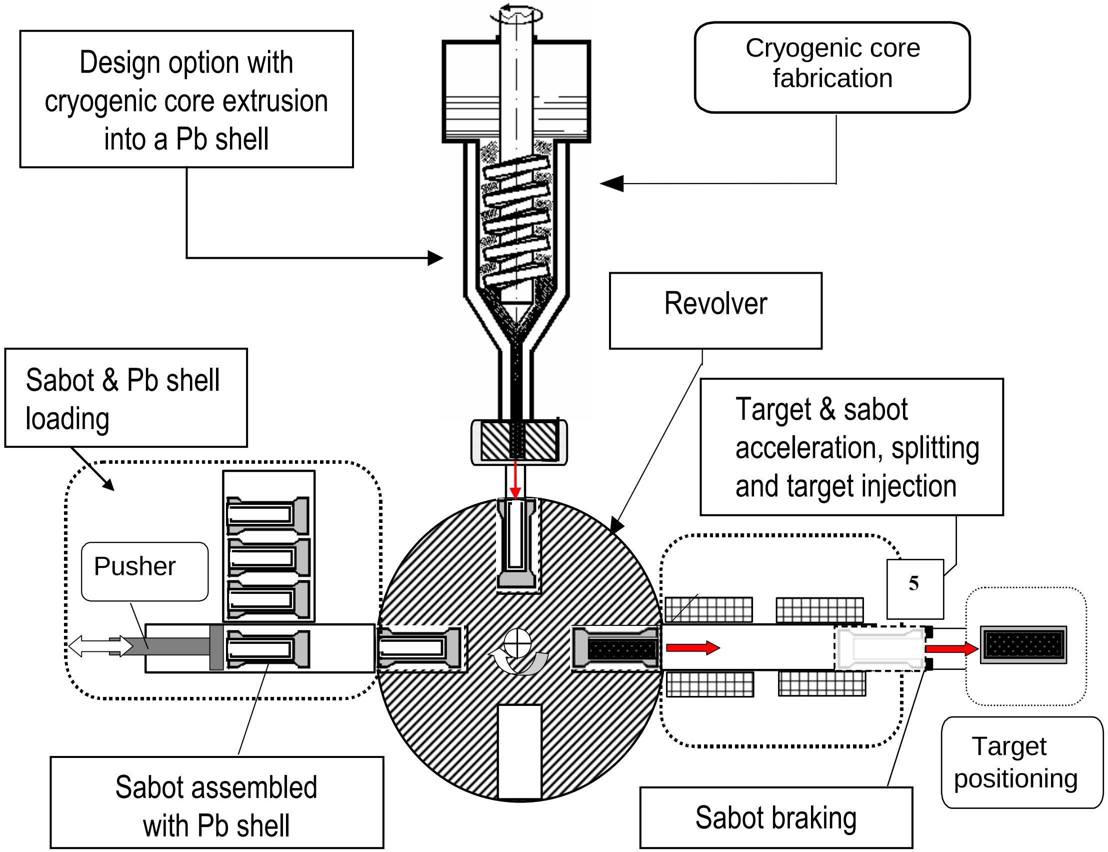
Schematic of the HEDgeHOB cryogenic target

[N.A.Tahir et al.Phys.Rev.E, 2000]

Pb shell of the HEDgeHOB target made by mold pressing

[the shell made under the contract between LPI, GSI & HEDgeHOB collaboration, 2007-2008]

System for the rep-rate fabrication and e-m delivery of the free-standing HEDgeHOB targets



Design option with cryogenic core extrusion into a Pb shell

Cryogenic core fabrication

Revolver

Sabot & Pb shell loading

Target & sabot acceleration, splitting and target injection

Pusher

Sabot assembled with Pb shell

Sabot braking

Target positioning

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