PROGRESS TOWARD RAPID FABRICATION AND SAFE DELIVERY OF DIRECT-DRIVE FREE-STANDING CRYOGENIC TARGETS

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THE ISSUES UNDER CONSIDERATION AT LPI WITH REGARD TO CRYOGENIC FUEL TARGETS

- ❑ **<u>Perfection and optimization of the free-standing target (FST) layering technique</u>, which is the cryogenic fuel layering inside moving free-standing capsules.** [this conf. I.V.Aleksandrova et al., Poster]

- ❑ **<u>Cryogenic target characterization</u>, including** [this conf. A.I.Nikitenko et al., 2 Oral reports; A.I.Kupriyashin et al. Poster]

  - Visual light tomography (3D reconstruction under multi-projection data processing)

  - Fourier holography (ultra fast characterization of the motionless or flying target)

- ❑ **<u>Cryogenic target delivery</u> using the injectors of different types, including** [this conf. E.R.Koresheva et al., Poster]

  - Gravitational injector

  - Electromagnetic injector (coil gun)

  - Combined injector: coil & gas gun

- ❑ **<u>Cryogenic target protection</u> during delivery process, including** [this conf. E.R.Koresheva et al., poster; I.V.Aleksandrova et al., poster]

  - Special protective measures optimization, which are the protective sabot (geometry & material), protective cover (geometry & material), and outer protective layers (reflective & ablative)

  - Application of the inherent survival features of fuel layer

OUTLINE

1. FST-based cryogenic system for 300-to-500 kJ multi-beams laser facility

The system design is based on our advances in the FST layering, characterization, and target delivery

2. Target survival during its delivery: inherent survival features of solid fuel layers with different structure

Our researches have shown that the fuel layers with isotropic ultrafine structure has maximal ability to survive under the delivery process

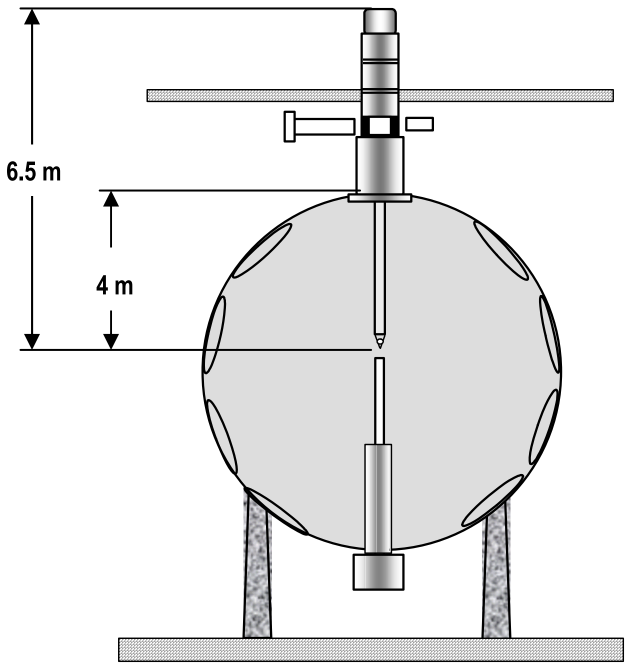
1. **FST-based cryogenic system for 300-to-500 kJ multi-beam laser facility**

SYSTEM FOR CRYOGENIC TARGETS FABRICATION & DELIVERY INTO THE CENTER OF 300-to-500-kJ LASER FACILITY (ISKRA-6, RUSSIA) IS AT THE STAGE OF DESIGN & ENGINEERING

[I.V.Aleksandrova et al. Fus.Technol. **38** N1, 2000; J.Phys.D: Appl.Phys. 2004; J.Russian Laser Research **2&3** 2007]

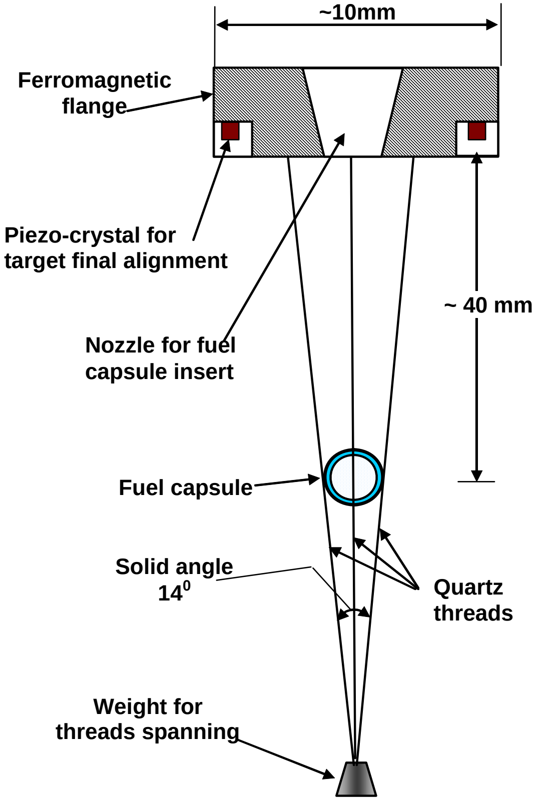
MAIN PRINCIPLES OF THE SYSTEM OPERATION

- DIFFUSION FUEL FILLING OF A BATCH OF FREE-STANDING SHELLS
- LAYERING PROCESS BASED ON THE FREE-STANDING TARGET (FST) TECHNOLOGY
- CRYOGENIC TARGET CHARACTERIZATION BASED ON TOMOGRAPHY -
- TRANSPORT PROCESS GOES GRAVITATIONALLY (FOR TARGET) AND ELECTROMAGNETICALLY (FOR HOLDER)
- TWO OPTIONS FOR TARGET POSITIONING AT THE CHAMBER CENTER ARE CONSIDERED: (1) TARGET INJECTION AND FREE-FALL, AND (2) TARGET ASSEMBLY WITH A HOLDER
- TARGET AND HOLDER ASSEMBLY GOES AT 10 K TARGET DELIVERY TO THE CHAMBER CENTER AT A RATE OF 1 PER HOUR

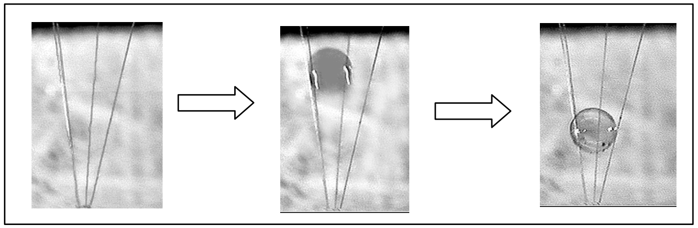


Target system geometrical arrangement in the reaction chamber of ISKRA-6 facility

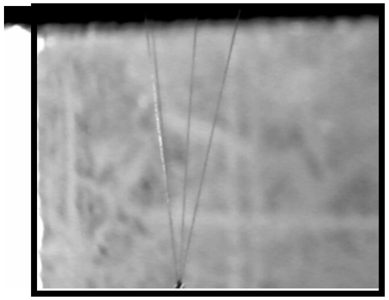
CRYOGENIC TARGET DESIGNS FOR ISKRA-6 EXPERIMENTS

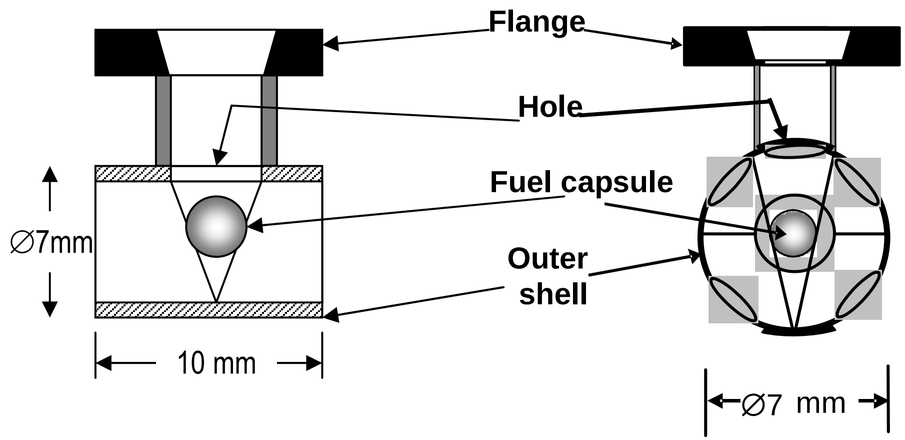


The holder in assembly with the direct-drive cryo target



The process of target/holder assembly





Indirect-drive cryo target assembly

OPTIMIZED DIRECT-DRIVE CRYO TARGET

[S.A.Belkov, S.G.Garanin, 2003]

Ignition (300 kJ):

CH shell, R = 1.46 mm, ΔR= 20 μm, W_{DT} = 15 μm

High gain (500 kJ):

CH shell, R = 1.54 mm, ΔR= 33 μm, W_{DT} = 23 μm

CRYOGENIC FUEL CORE FOR INDIRECT-DRIVE TARGET

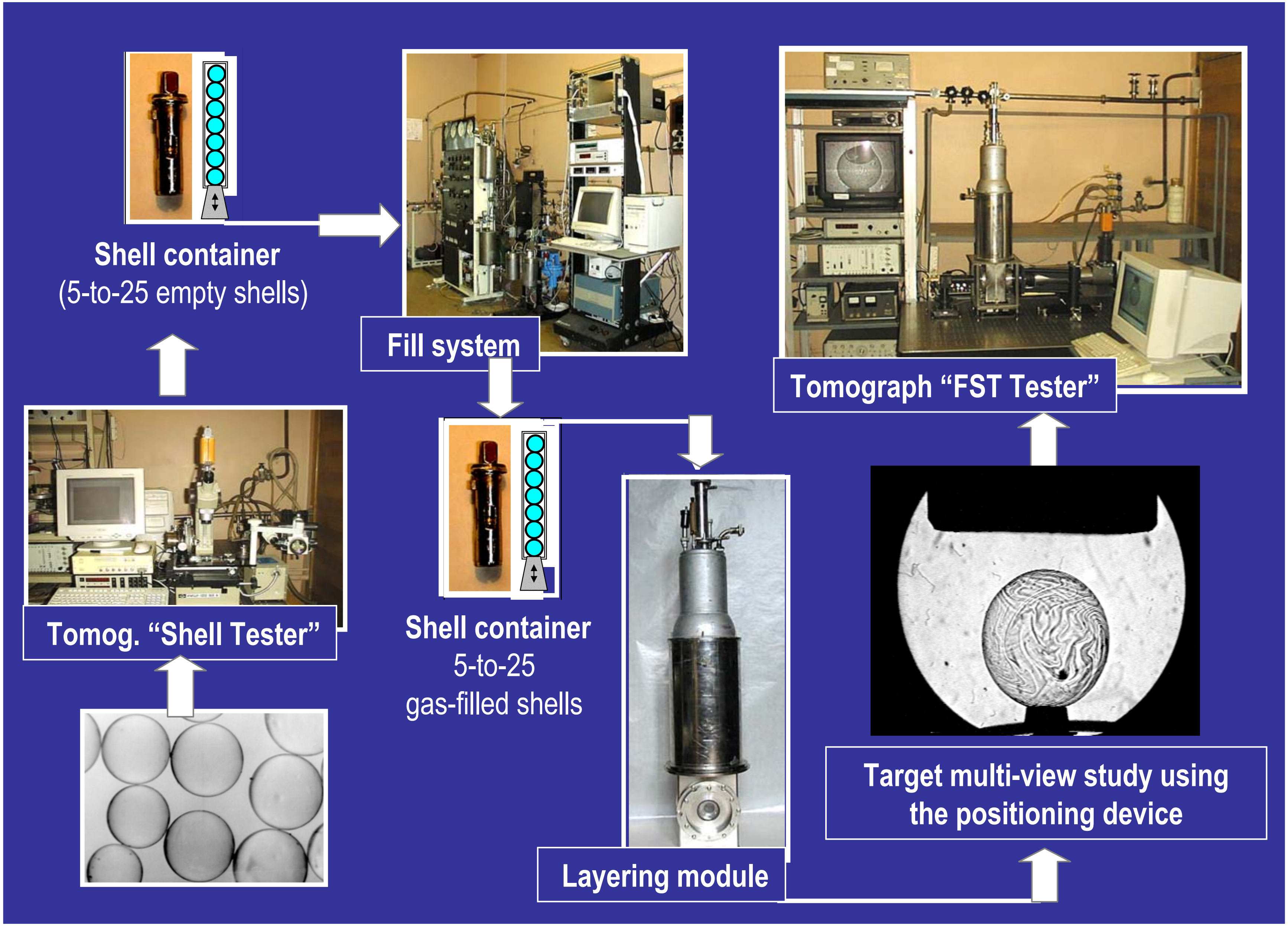
CH shell:

2R = 1.0÷1.6 mm, ΔR= 27÷70 μm, W_{DT} = 12÷40 μm

Glass shell:

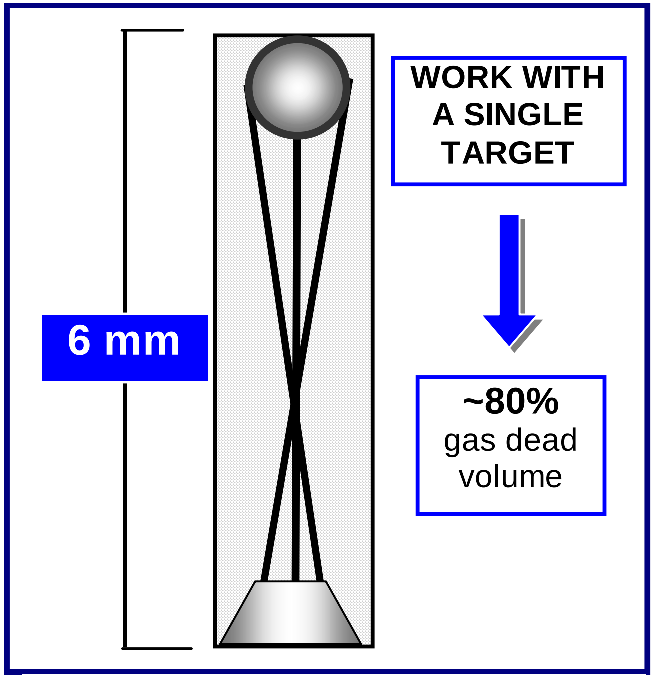
2R = 1.0÷2.0 mm, ΔR= 15÷50 μm, W_{DT} = 10÷50 μm

FREE-STANDING TARGET FACILITY CREATED AT LPI HAVE BEEN USED TO DEMONSTRATE THE OPERATIONAL PRINCIPLES OF THE DESIGNED SYSTEM (for CH shells of ∅ 0.8-1.8 mm)

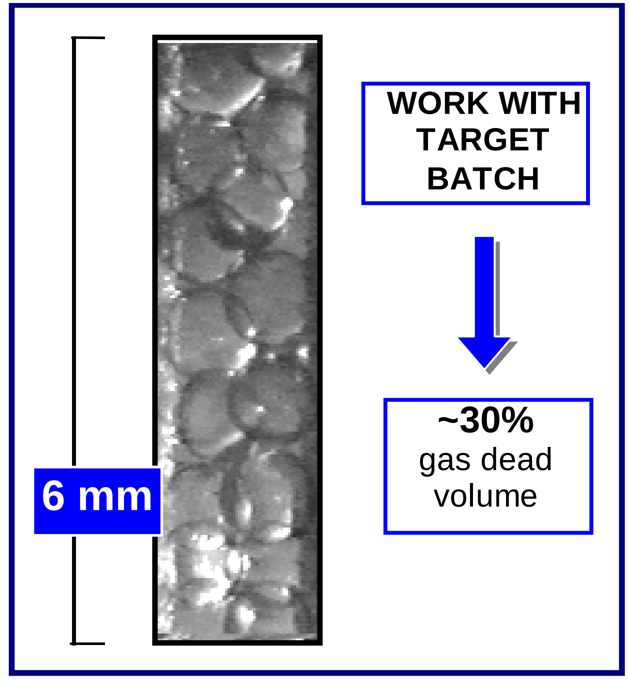


SHELLS FILLING WITH GASEOUS FUEL.

Schematic of the shells disposal inside a permeation cell (shell container)



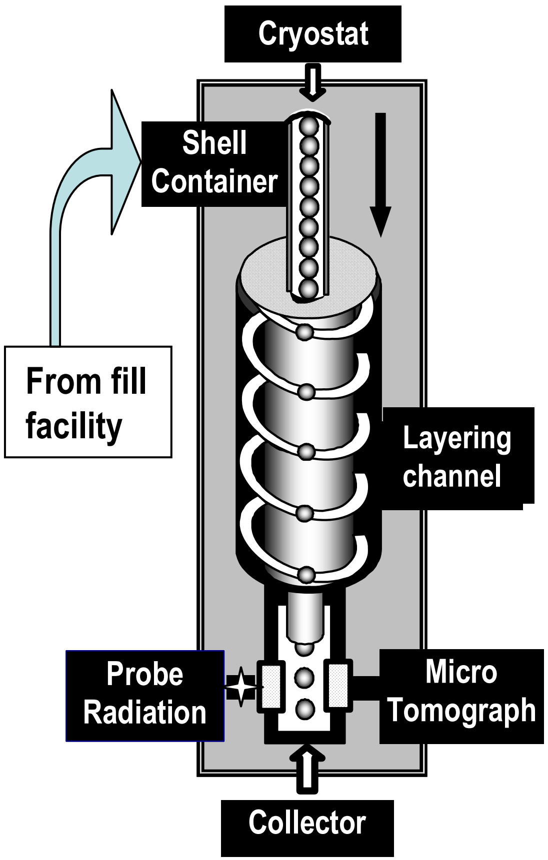
PRE-MOUNTED TARGET APPROACH



FREE-STANDING TARGET APPROACH

The FST approach ensures
(a) minimal filling time per 1 target,
(b) minimal dead volume of gas in the permeation cell, and
(c) transport of an array of gas-filled shells to the layering module at 300 K

MAIN PRINCIPLES OF THE FST LAYERING MODULE OPERATION



FST layering module with a spiral layering channel

[see movie]

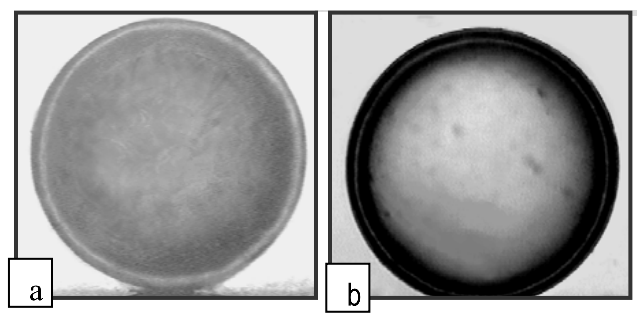
For achieving successful layering results, proper allowance must be made for the following:

– targets must be unmounted (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

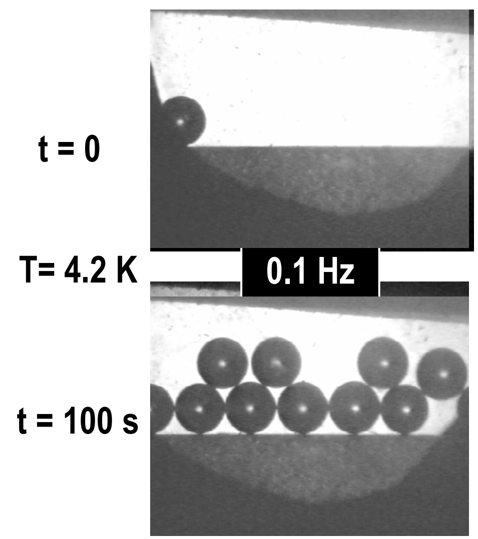
– transport process is target injection between shell container – layering module – collector.



The layering results obtained by FST technique

a)CH shell OD 1.5 mm, D2 layer 50 mm thick (3 % Ne additive)

b)CH shell OD 1.2 mm, D2 layer 41 mm thick (20 % Ne additive)



Repeated target injection from the layering module to the collector

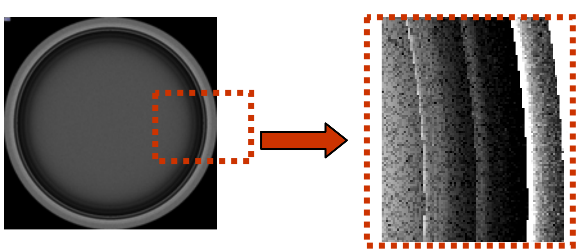
CRYOGENIC TARGET TRANSPORT TO TOMOGRAPHIC TEST CHAMBER FOLLOWED BY ITS CHARACTERIZATION (has been developed and demonstrated under the ISTC Project #1557)

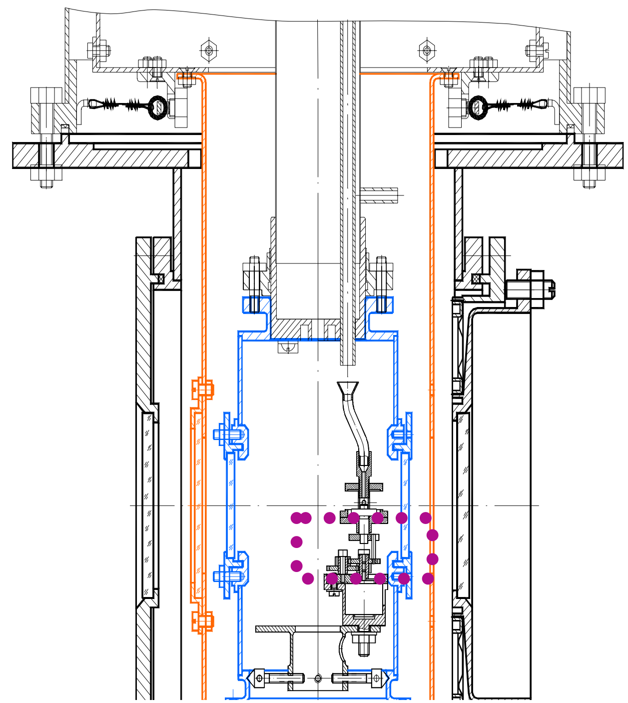
1. **Cryogenic target transport under gravity from the layering channel to a drive shaft of target positioning device**
2. **Cryogenic target scanning goes under the following conditions:**

- **Target rotation around vertical axis (cryostat and source of probe radiation are fixed)**
- **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 1-2 μm (in one proj.)**

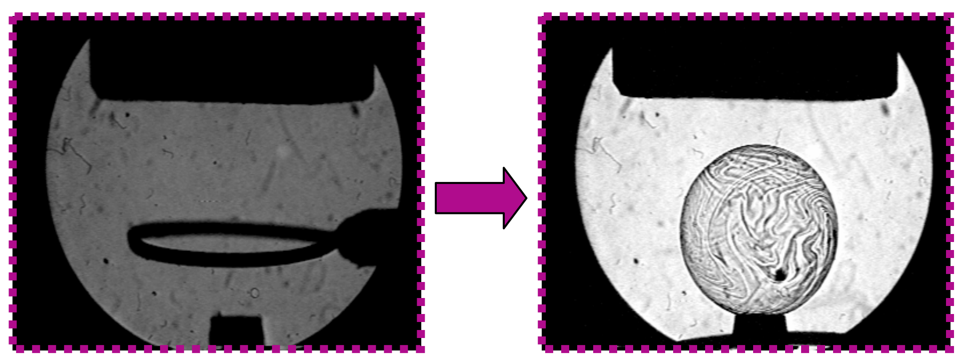
3. **Projection data processing using a software package *Target Studio* developed at LPI.**

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





Target positioning device inside tomographic test chamber



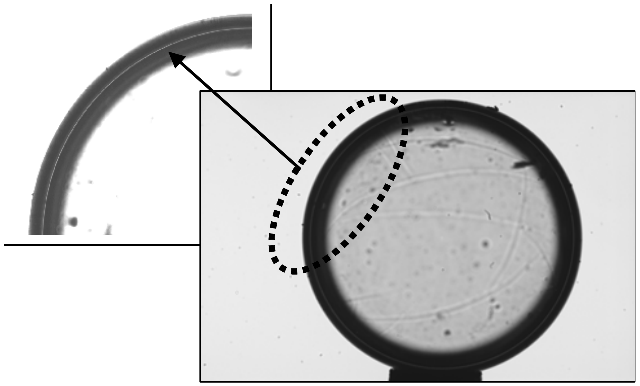
STAGE OF CRYOGENIC TARGET CHARACTERIZATION

A special developed software *TARGET STUDIO* to be used for characterization of a cryogenic target using 30-to-100 shadow projections. [E.R.Koresheva, A.I.Nikitenko et al. Nuclear Fusion, 2006]

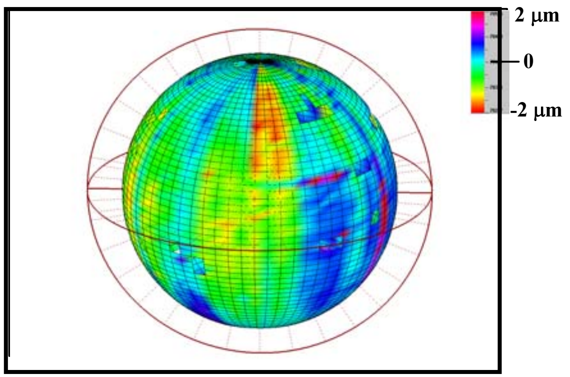
Bright band position analysis

TARGET PASSPORT

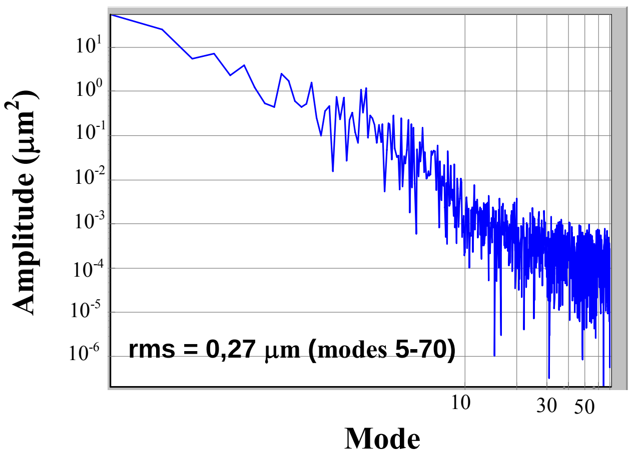
Outer surface	
Mean radius::	712.4
Min radius ::	710.3
Max radius ::	716.7
Out-of-roundness::	0.4 %
Inner surface	
Mean radius::	690.9
Min radius::	687.3
Max radius ::	694.1
Out-of-roundness::	0.5 %
Wall parameters	
Mean thickness::	21.5
Min thickness ::	17.7
Max thickness ::	25.6
Nonuniformity::	19.0 %



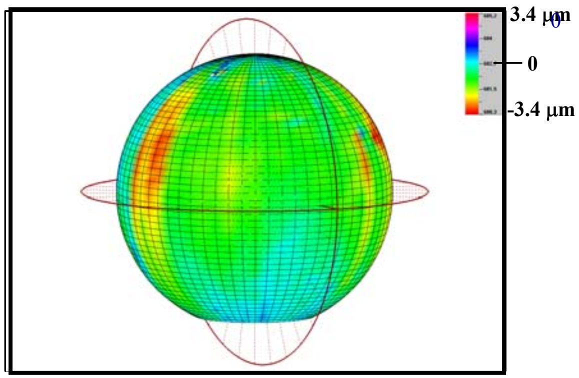
CH shell shadow projection



CH shell outer surface (reconstructed)



Fourier spectrum of the bright band

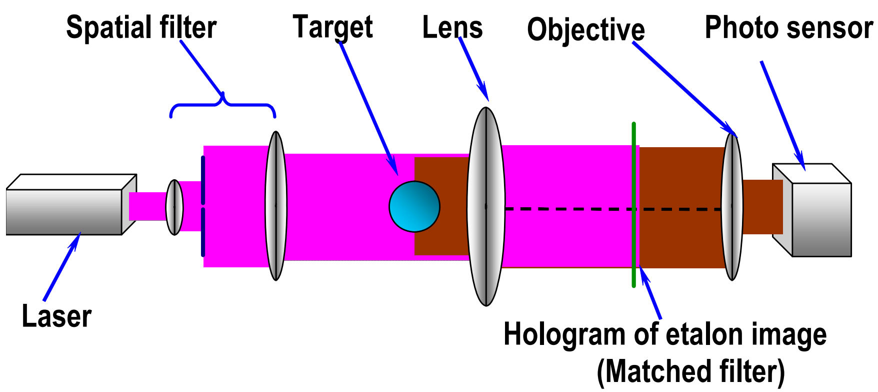


CH shell inner surface (reconstructed)

Result of 3D reconstruction of the free-standing CH shell using 90 shadow projections

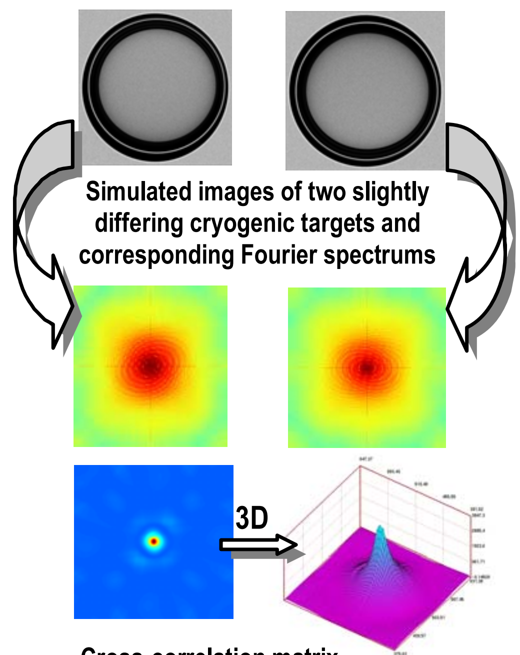
FOURIER HOLOGRAPHY OF IMAGE RECOGNITION TO BE USED AT THE STAGE OF CRYO TARGET FINAL CHARACTERIZATION JUST BEFORE ITS IRRADIATION. **This approach has been proved in a number of computer experiments using a special developed software hologram** [Nuclear Fusion, 2006]

- 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
- 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



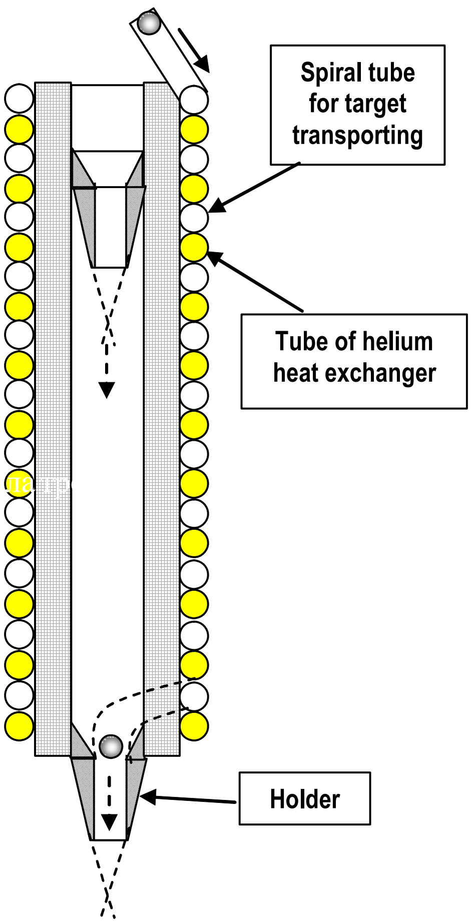
RESUME ON THE MODELING RESULTS

- The scheme can be used both for flying and fixed target as well as both for single target and target massive
- The scheme can be used for simultaneous control of a number of parameters of the flying target, namely: non-uniformity and roughness, velocity and trajectory

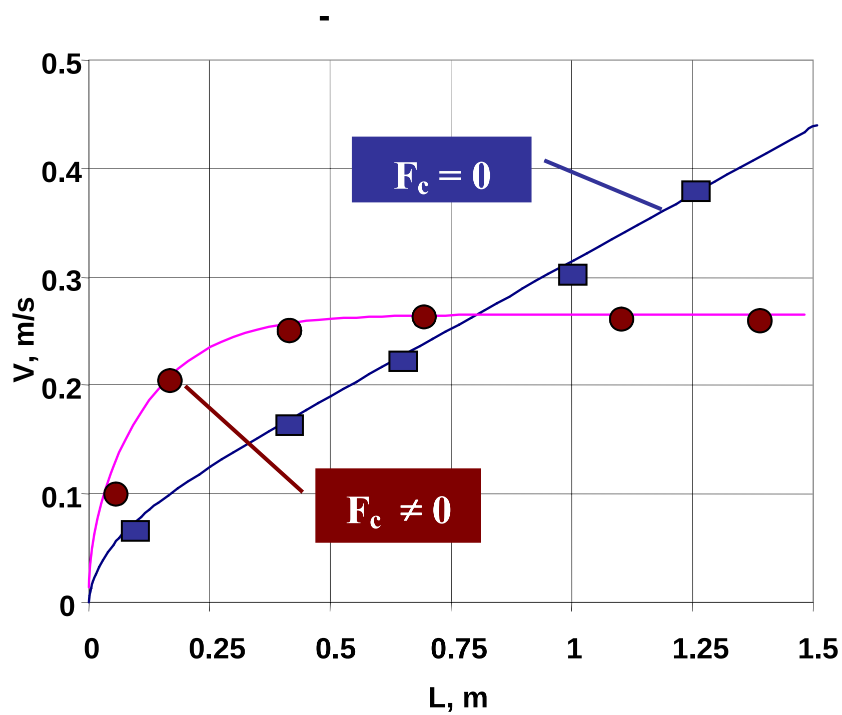


Cross-correlation matrix of the images

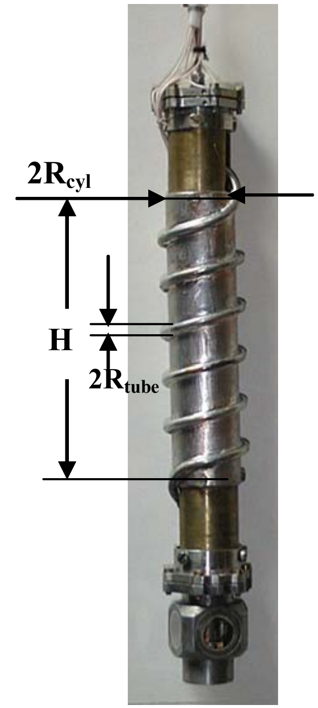
TRANSPORTING CHANNEL: Target pass under gravity through a spiral channel. The holder motion and positioning is controlled electromagnetically. Such an approach allows irradiation (in different experiments) of both free-fall target and target fixed on a holder.



A schematic option of target and holder transporting channel.



Target velocity hold is achieved by action of centrifugal force (Fc)



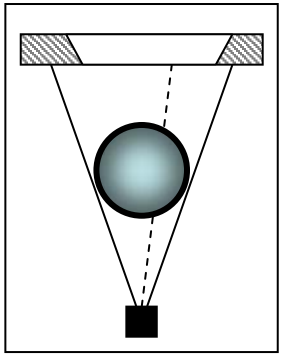
General view of a spiral channel

Our estimations have shown that the optimal direct-drive target for 500 kJ at ISKRA-6 will acquire 0.3 m/sec of a constant velocity at a length of 0.53 m (for $\alpha=15^0$ and $2R_{cyl}$=53 cm). Such a velocity will exclude the target destruction at an abrupt braking.

*/The full length of a spiral transporting tube is >> 1 m

A SCHEMATIC OF THE FST SYSTEM FOR CRYOGENIC TARGETS FABRICATION AND DELIVERY TO THE CENTER OF TARGET CHAMBER. CRYO TARGET & HOLDER ASSEMBLY GOES AT 5÷10 K

APPLICATION OF FREE-STANDING TARGET TECHNOLOGY ALLOWS TO CONSIDER 3 OPTIONS:

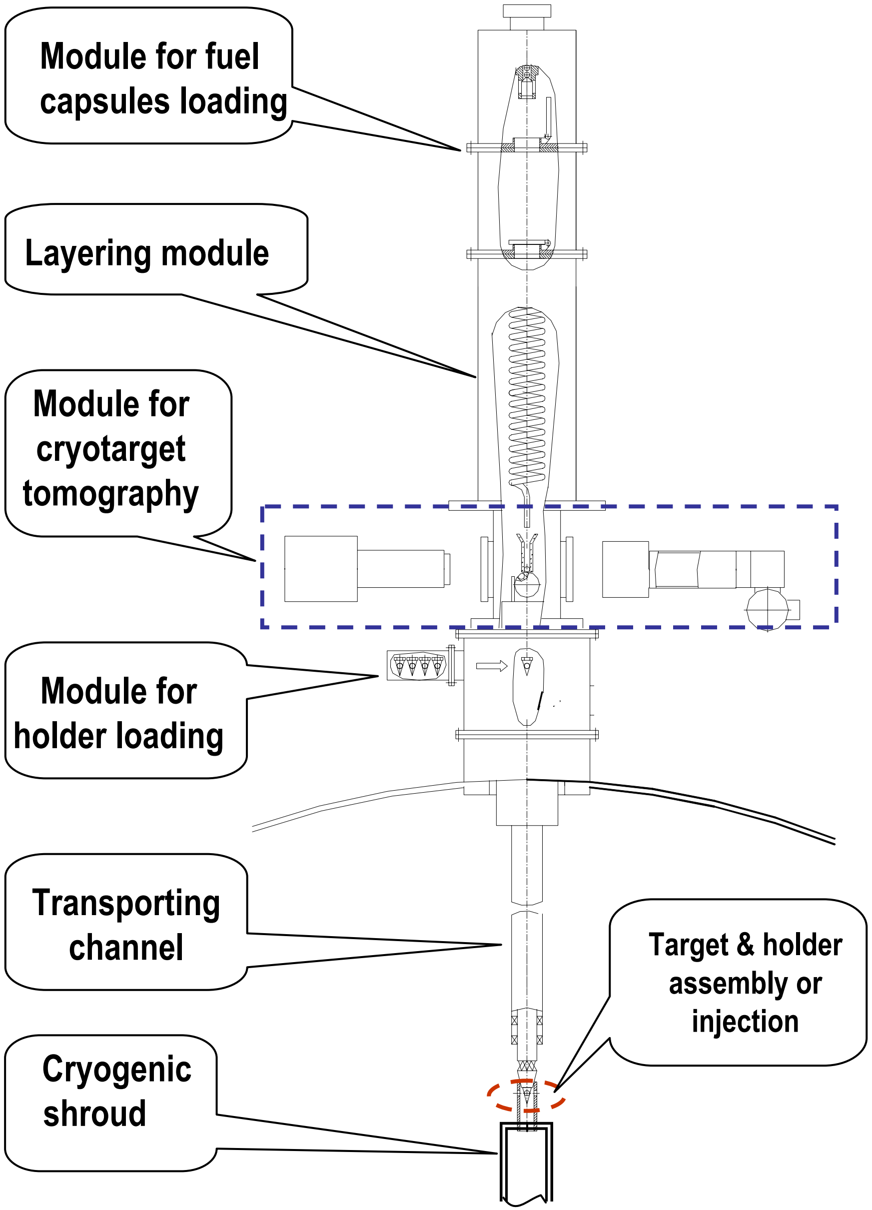


OPTION 1: target/holder assembly at the module for holder loading

OPTION 2: target/holder assembly at the chamber center

OPTION 3: Target injection from the transport channel into the chamber

The test model of the FST system (working at room temperature level) will allow to make a final decision concerning the most promising option of target delivery and positioning at the chamber center.



2. TARGET SURVIVAL DURING ITS DELIVERY:

a comparative analysis of the inherent survival features of fuel layers with different structure

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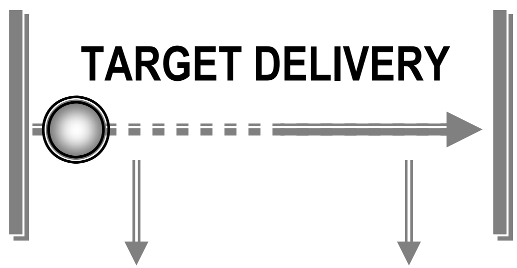
LAYERING MODULE

1. Non-uniformity: NU < 2 %
2. Roughness: δ < 0.5 μm
3. Temperature: T< T_{TP} (19,7K for DT)



MOMENT OF IRRADIATION

1. Non-uniformity: NU < 2%
2. Roughness: δ < 0.5 μm
3. Temperature: 18.5 K (for DT)

ACCELERATION $\rightarrow$ FLIGHT

OVERLOADS
- Mechanical damage of target components

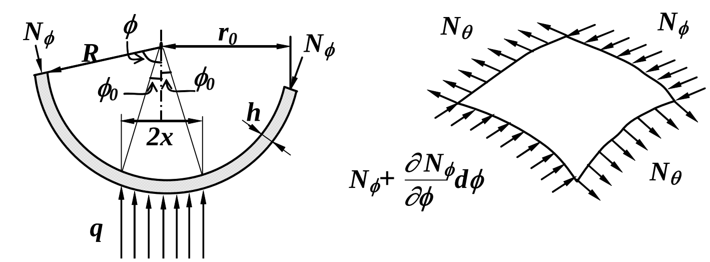
HEAT LOADS
- Fuel layer distortion in high & low modes
- Fuel overheating

CRYOGENIC FUEL LAYER STRENGTH MODELING: Modeling results have shown that one of the key parameters, defining the value of permissible overloads on a shell is the (σ/ρ) ratio

The strength modeling is based on a zero-moment theory developed by S.P.Timoshenko [Theory of Plates and Shells. 1969].

R>>h

The distribution of forces in the spherical shell section under axial loading *q*



1. The equation of shell top equilibrium during the axial loading:

   $2\pi r_0 N_\varphi \sin\varphi + qR^2\pi \sin^2\varphi_0 = 0$ and $N_\varphi = - N_\theta = - (qR \sin^2\varphi_0)/ 2\sin^2\varphi$

2. The maximum stretching line force N_θ will be at $\varphi = \varphi_0$ (i.e., at the periphery of the area of contact with a radius *x*) $N_0 = qR/2$

3. The maximum tensile strength inside the wall of a shell $\sigma = N_0/h = qR/2h = PR/(2\pi x^2 h)$, where ***P*** is the force, which corresponds to the beginning of shell destruction, $P = ma = a\rho V$

4. It is follows from the above, that $a/g = A(\sigma/\rho)$

   where ***A*** is defined by the conditions of the experiment (temperature, geometry), σ and ρ are tensile strength and density of shell material, correspondingly

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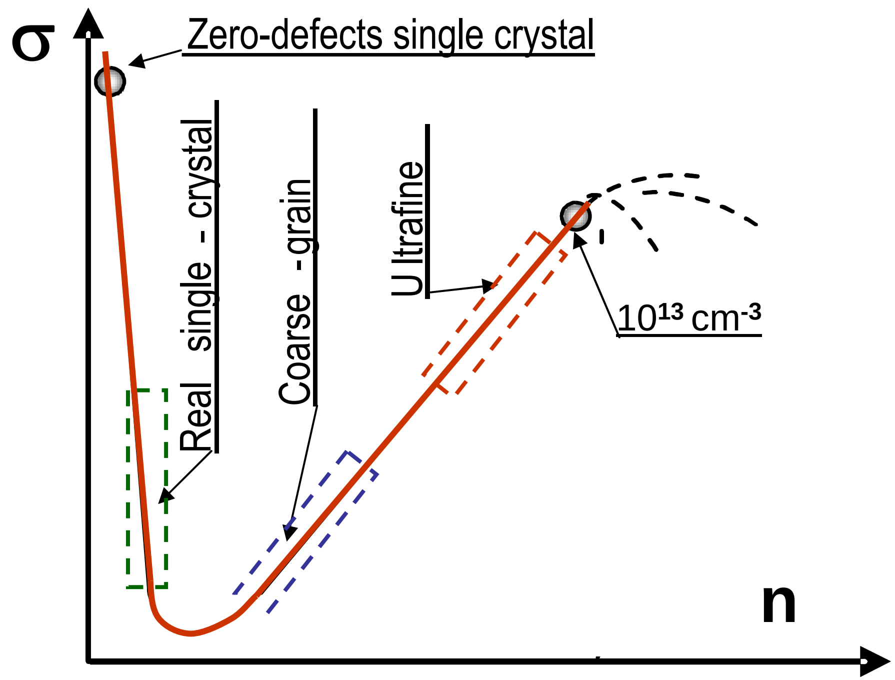
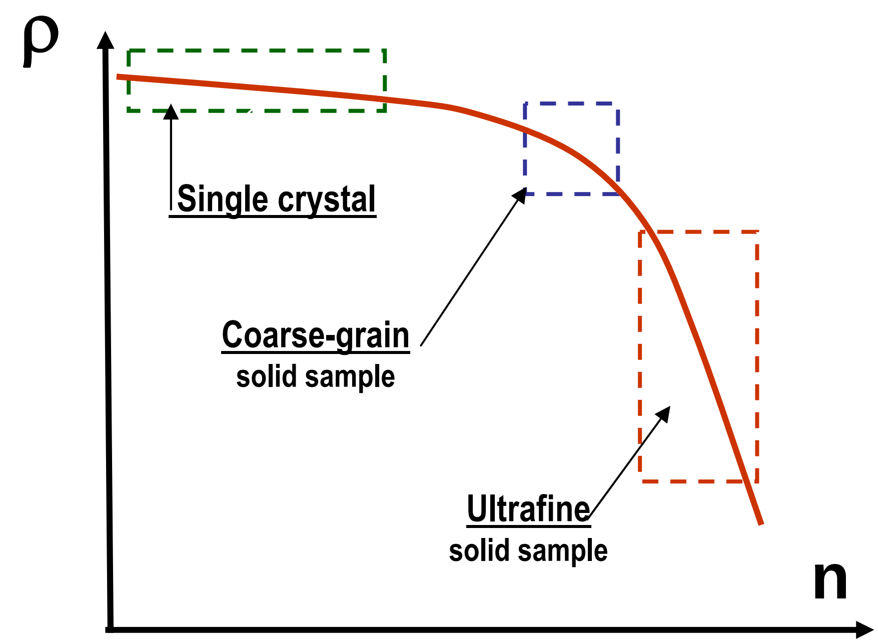
Since the destruction limit during the short-term load is always higher then during the static one, the above formula evaluates a lower limit of permissible overload

ULTRAFINE FUEL LAYER CAN WITHSTAND HIGHER OVERLOADS THAN THE CRYSTALLINE ONE AS THE RATIO (σ/ρ) FOR ULTRAFINE LAYER IS MAXIMAL



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

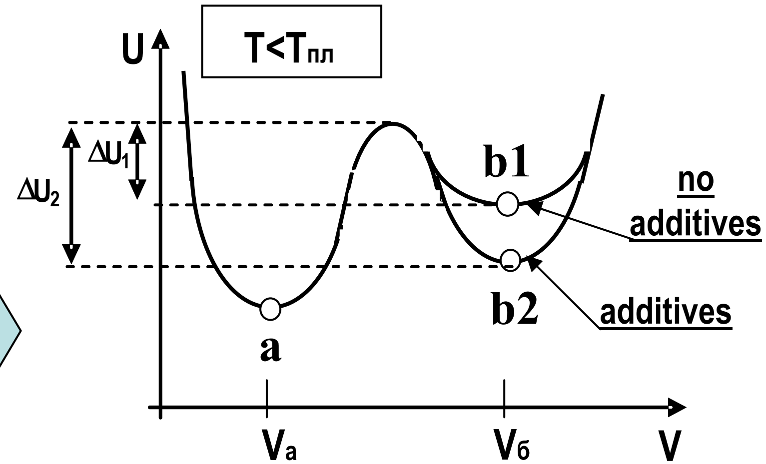


Sample density (ρ) vs. defect density (n)

- Ultrafine material contains of 20-to-60% of grain boundary phase with the reduced density ρ
- In the contrast to coarse-grain crystal material, an ultrafine material has no planes of low glide dislocations. This is one of the reasons of higher mechanical strength σ of ultrafine material than of the crystalline one.
- Yield strength σ_m for material with a grain size d is given by the Petch-Hall equation: $\sigma_m = \sigma_0 + Kd^{-1/2}$. Thus, the smaller d (the higher defect density n), the higher σ_m .

HYDROGENS IN THEIR EQUILIBRIUM STATE ARE MOLECULAR CRYSTALS. SOLID FUEL LAYER IN ULTRAFINE STATE IS META-STABLE. OUR EXPERIMENTS HAVE DEMONSTRATED THAT THE USE OF A SPECIAL DOPING ALLOWS TO STABILIZE THE META-STABLE LAYER

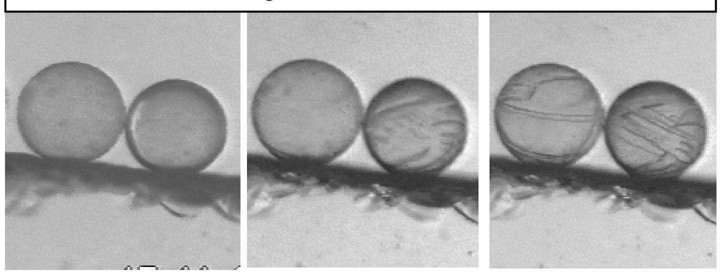
- It is well-known, that insertion into a substance of special dopings makes it possible
  - (a) to increase a dispersity level of a substance
  - (b) to increase stability of a high dispersed substance
- Due to an additive interaction with the defects of structure, elastic energy of the given structural state decreases: potential well becomes deeper, and power barrier ΔU becomes higher.
- Our experiments have demonstrated that using high temperature additives (for example, using HD as additive to H2 and Ne as additive to D2) allows forming thermo-stable solid cryogenic layer in high dispersed (ultrafine) state.



(a) stable crystalline state;

(b1,b2) metastable high-dispersed state

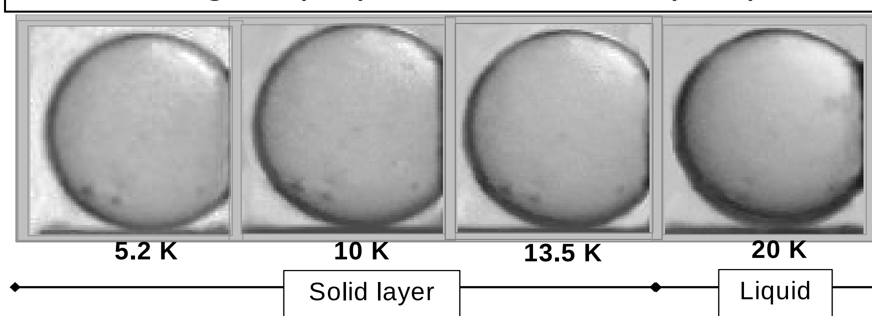
H2-layer; no additives



4.2 K 5.0 K 6 K

Ultrafine solid H2-layer re-crystallization under target heating to 5-6 K

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



Ultrafine solid layer does not convert into coarse-grained crystal state under target heating in the range of 5 K - T_{tp}

TARGET FLIGHT (1): UNIFORM HEAT FLUX, ANISOTROPIC & ISOTROPIC FUEL LAYERS

❑ SURVIVABILITY OF FUEL LAYER UNDER HEAT LOADS DEPENDS ON THE LAYER STRUCTURE

- **In their equilibrium state the solid isotopes of hydrogen are of anisotropic molecular crystals. In this case the sound speed depends on sound wave line about the crystallographic axes. The difference in sound speed for single H_2-crystal makes up to ~ 19%** [R.Wanner,1972]
- **In the molecular crystals the mechanism of heat conduction is mainly connected with lattice conductivity, which is in direct proportion to the value of sound speed (Debye`s theory):** $k \sim (1/3)Cv\Lambda$
- **Therefore, even under condition of uniform heat flux, the inner surface of anisotropic fuel layer becomes non-isothermal, which initiates the fuel migration in the target cavity and results in the layer degradation in term of thickness and roughness.**

❑ COOLING RATE IS A KEY MOMENT IN FORMING FUEL LAYERS WITH A GIVEN STRUCTURE

- **Extremely high cooling (FST layering) results in a creation of an ultimate disordered structure with a large defect density (isotropic ultrafine medium)** [J.Phys.D:Appl.Phys. 37, 2004]:

  layering time <15 sec, cooling rate 1-to-10^2 K/sec

- **In the case of extremely slow cooling (traditional approach) the fuel layer is formed in the stable macro-crystalline state (anisotropic medium)** [LLE Review, QR 99, 2004]:

  layering time > 5 hrs, cooling rate ~10^{-5} K/sec

TARGET FLIGHT (2): modeling of the process of anisotropic fuel layers degrading due to thermal radiation in the reaction chamber (uniform heat flux) [This conf. I.V.Aleksandrova et al. Poster]

- **ISOTROPIC FUEL LAYER: the heat conductivity coefficient does not depend on spatial co-ordinates; there is no reason for surface roughness arising in the condition of uniform heat flux**

- **ANISOTROPIC FUEL LAYER: the heat conductivity coefficient is a vector quantity, which components in the spherical coordinates can be written in the form**

$$k_1 = k_s \cdot (1+\xi_1(\varphi,\theta)),\, k_2 = k_s \cdot (1+\xi_2(\varphi,\theta)),\, k_3 = k_s \cdot (1+\xi_3(\varphi,\theta))$$

where $\xi_1(\varphi,\theta)$ - dimensionless function, which describes a variation of the heat conductivity coefficient in different directions;

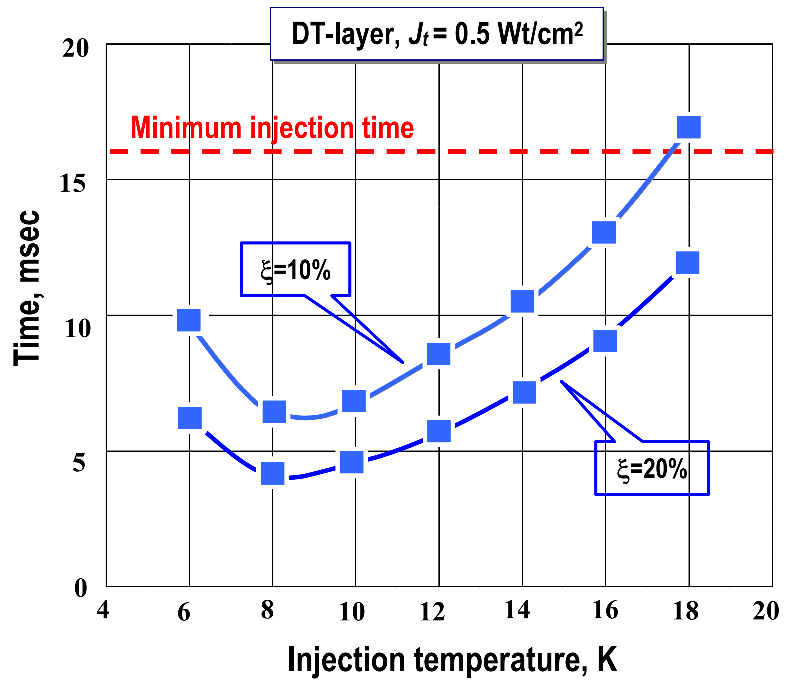
ξ_l = 0 for isotropic layers only

- **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**

CALCULATION RESULTS (UNIFORM HEAT FLUX): ANISOTROPIC FUEL LAYER DEGRADES BEFORE THE MOMENT OF TARGET ARRIVAL AT THE CENTER OF REACTION CHAMBER. TO SOLVE THE PROBLEM ONE SHOULD APPLY TARGETS WITH ISOTROPIC FUEL LAYER.

Time for surface roughness growth up to 0.5 μm, msec

ξ_1, %	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



■ Calculation results present the time of surface roughness growth from a zero level to 0.5 μm under variation of the layer anisotropy (ξ_1) and the heat flux absorbed during injection (J_t)

■ 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.

RESUME ON THE MODELING RESULTS

- **Acceleration stage:**
  - The parameter σ/ρ defines the value of permissible overloads on a shell and fuel layer
  - The ratio σ/ρ is maximal for fuel layer being in an ultrafine state, and minimal for real crystal
  - <u>Thus, the ultrafine fuel layer can withstand higher overloads than the crystalline one</u>

- **Target in flight (uniform heat flux):**
  - Anisotropic fuel layer (ξ=10-to-20%) degrades before the moment of target arrival at the center of reaction chamber.
  - <u>Isotropic fuel layer does not degrade</u>

- **An isotropic ultrafine fuel layer (i.e. fine-grained, nano-structured or amorphous one) has necessary inherent survival features for both stages of target injection.**

NANO-LAYERING TECHNOLOGY DEVELOPMENT IS A KEY POINT IN TARGET SURVIVAL PROBLEM

FST LAYERING TECHNOLOGY DEVELOPED AT LPI CAN BE USED AS A BASE FOR NANO-LAYERING TECHNOLOGY DEVELOPMENT

[E.R.Koresheva et al. Report on the implementation of the IAEA Project N13871/R0, 2007]

Extremely high cooling rate (1-to-100 K/s)
+
High-melting additives in the range of 3% - 20%

- **High mechanical strength and thermal stability**
- **The FST method holds much promise for the stable ultrafine cryogenic layer formation from DT-mixture, in which the amount of tritium is 10-20%. Tritium here stands as a high-melting additive relative to deuterium.**

The total layering time is less than 15 seconds

- **It is a determining factor in the view of tritium inventory minimization**

FST layering method demands to use free-standing targets in each production step.

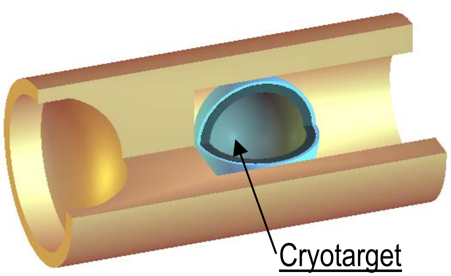
- **Rep-rated target production and delivery (currently 0.1 Hz). Prospects for target injection at a rate of about 10 targets per second.**

FOR SUCCESSFUL DELIVERY OF CRYOGENIC TARGET AT THE CENTER OF REACTION CHAMBER IT IS NECESSARY THE JOINT APPLICATION OF A CERTAIN PROTECTIVE MEASURES AND THE INHERENT SURVIVAL FEATURES OF ULTRAFINE FUEL LAYER

PROTECTIVE MEASURES at the stage of TARGET ACCELERATION

[I.E.Osipov et al, IFSA-2001, Kyoto]

1. OPTIMAL SHAPE OF TARGET NEST
2. OPTIMAL MATERIAL OF SABOT
3. OPTIMAL TEMPERATURE OF TARGET HANDLING



PROTECTIVE SABOT WITH A TARGET IN THE NEST

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NEW: Application of the inherent survival features of an ultrafine fuel layer

[This conf., I.V.Aleksandrova et al. Poster]

AN ULTRAFINE FUEL LAYER can withstand to higher overloads and higher heat loads than a crystalline layer.

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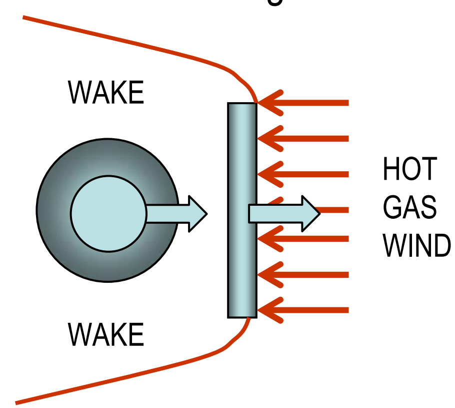
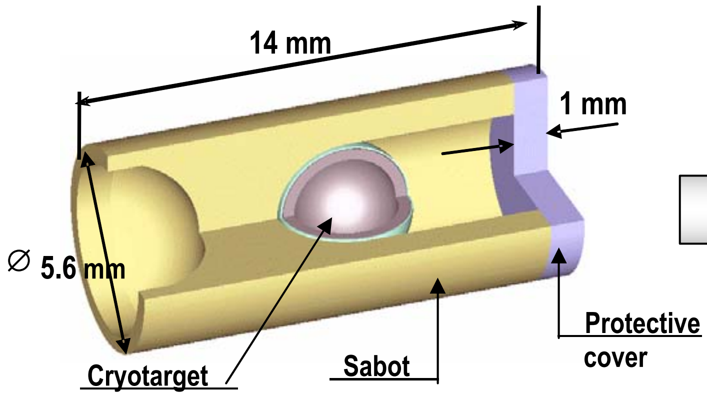
PROTECTIVE MEASURES at the stage of TARGET FLIGHT

[I.E.Osipov et al, IFSA-2001, Kyoto]

1. OUTER PROTECTIVE LAYERS (METALLIC, ABLATIVE)
2. PROTECTIVE COVER (SHROUD): the cover forms a wake area in the fill gas to avoid convective heating



AN EXAMPLE OF JOINT APPLICATION OF THE PROTECTIVE MEASURES AND THE INHERENT SURVIVAL FEATURES OF FUEL LAYER [I.E.Osipov et al. IFSA, 2001; E.R.Koresheva, IAEA-RCM 2002 & 2003]



"Cryotarget & sabot & cover" assembly

RESULTS OF OPTIMIZATION OF THE "ASSEMBLY" COMPONENTS:

- ❑ Target nest geometry: flat bottom with the conical hole
- ❑ Sabot material: magneto-insulator with 60-to-80% of the ferromagnetic part
- ❑ Protective cover material: solid D_2 or Xe
- ❑ Target acceleration at 5 K
- ❑ FST-layering optimization:

- Initial target temperature: 3-5 degree above Ttr
- Cooling rate: 1-to-50 K/sec
- Additives: high triple point hydrogen isotopes, 3-to-20 %

THE "ASSEMBLY" COMPONENTS PURPOSE

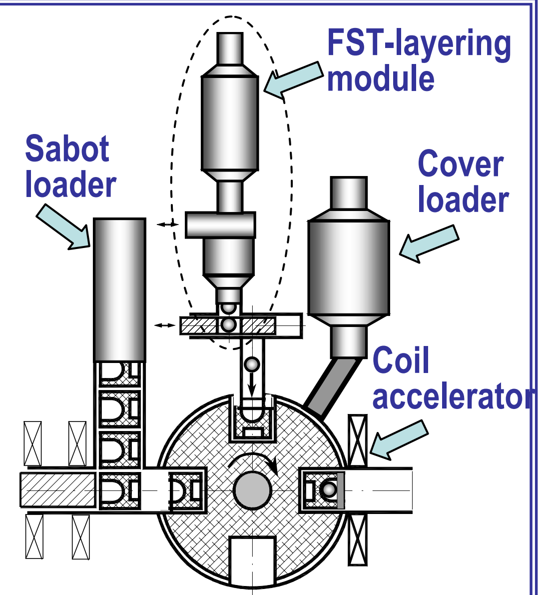
❑ Sabot allows to transmit effectively an acceleration impulse to the target, and to protect the target from damage during the acceleration process.

❑ Protective cover co-injected with target into reaction chamber allows to protect cryo target from the head wind during its flight inside reactor chamber

❑ Fuel layer inside free-standing target is formed in ultrafine state using the FST-layering

CONCEPT OF A HIGH REP-RATE CRYOTARGET FACTORY (0.1-to-10 Hz)

[see movie]



Elena R. Koresheva