# CONCEPTION of a CRYOGENIC TARGET FACTORY for IFE


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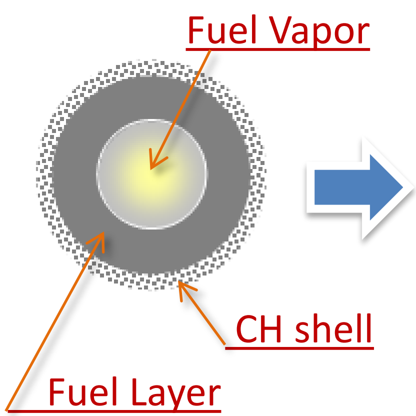
# Cryogenic Target Factory is one of the main building blocks of IFE reactor

**Principle of CTF operation: targets must be free-standing at each production step**

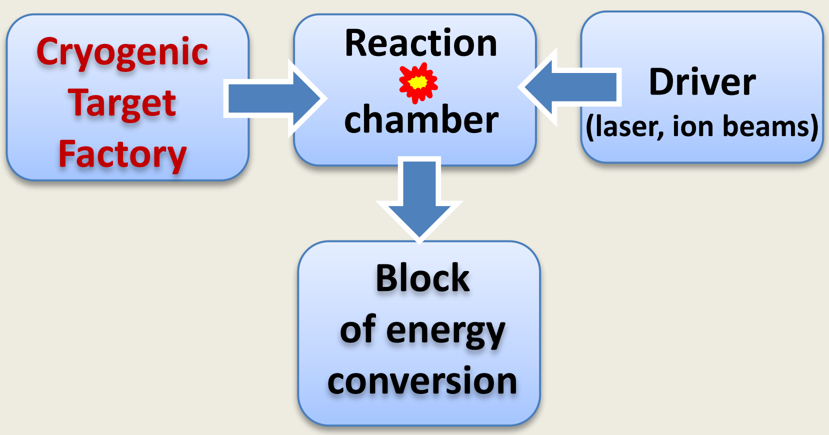
## Direct-drive Cryogenic Fuel Target




**Fuel layer specifications**

- **Thickness non-uniformity: Nu < 1.0%**
- **Inner surface roughness: δ < 1 um** rms in all modes

## Main building blocks of IFE reactor




## Cryogenic Target Factory Specifications

**1. Free-standing targets mass-production:**
~ 500000 targets/day (upon the average)

**2. High rep-rate target delivery:** targets must be delivered to IFE chamber at a rate of 1-10 Hz (laser or heavy ion drivers) or 0.1 Hz (Z-pinch)

**3. Survivability of a fuel core during target delivery:**
– Layers with inherent survival features
– Multiple target protection methods

**4. On-line target characterization in IFE chamber:** Quality & Trajectory

**5. Assembly of different elements:**
- Target elements → hohlraum target, FI target
- Target-&-sabot
- Layering module-&-injector

**6. Tritium inventory minimization**

# The Lebedev Physical Institute (LPI) propose the conception of a Cryogenic Target Factory (CTF) for IFE

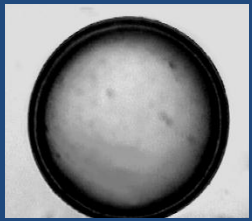
**The CTF is based on the approaches proposed & examined at LPI [1]:**

**(a) Free-standing targets (FST) technology for a high rep-rate & cost-effective operation of the CTF [2]**

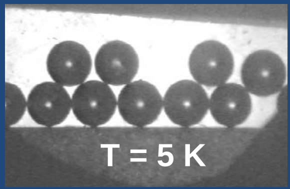
**(b) Magnetic levitation (maglev) transport systems for almost frictionless motion of the cryogenic targets at their handling [3]**

**(c) Fourier holography for *on-line* characterization & tracking of a flying target [4]**

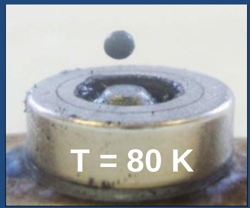
**The POP and computer experiments have proved the interaction efficiency of the proposed approaches**



**FST –layering : free-standing cryo target**




**Targets injection with the rate of 0.1Hz** (batch mode)




**HTSC coated CH shell levitating above magnet**

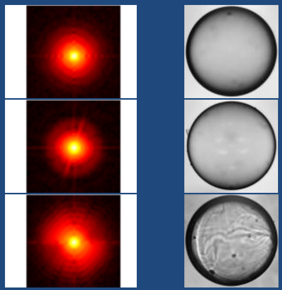


**Image Fourier transforms of the shells with different imperfections**


1. Osipov I.E. et al. *Pilot Target Supply System Based on the FST Technologies: Main Building blocks, Layout Algorithms and Results of the Testing Experiments.* Plasma & Fusion Res. **8** (2), 2013
2. Aleksandrova I.V. et al. *An efficient method of fuel ice formation in moving free standing ICF / IFE targets.* J.Phys. D: Appl.Phys. **37**, 2004
3. Aleksandrova I.V. et al. *HTSC maglev systems for IFE target transport applications*. J. Russian Laser Research **35**(2), 2014
4. Koresheva E.R. et al. *Possible approaches to fast quality control of IFE targets.* Nuclear Fus. **46**, 2006

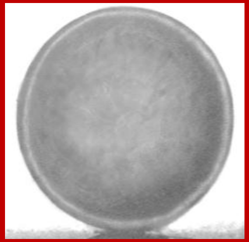
# CTF prototype created and tested at LPI for targets under 2 mm-diam: CURRENT PARAMETERS

- **Formation of cryogenic layers inside moving free-standing CH shells of ∅ 0.8-1.8mm**
- **Formation of isotropic ultra-fine cryogenic layers to meet the requirements of implosion physics:**

– Enhance mechanical strength and thermal stability which is of critical importance for target fabrication, acceleration and injection

– Avoid instabilities caused by grain-affected shock velocity variations

CH shell ∅ 1.5 mm;
50 um-thick cryo layer
Cryo layer components: 97%D2 + 3%Ne
CH shell is covered by outer layer from Pt/Pd (200 Å)



- **Tritium inventory minimization in the CTF:**

– Minimal spatial scale due to close packing of free-standing targets

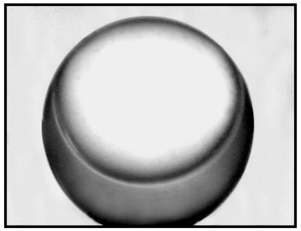
– Minimal layering time: **$t_f$ < 15 sec** (conventional production methods: **$t_f$ ~ 24 hrs**)

– Minimal transport time between the basic units of the CTF due to realization of injection transport process

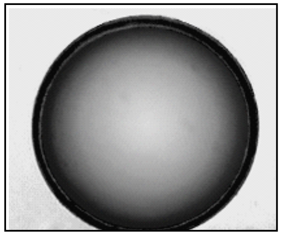
- **Rep-rate mode of the CTF operation:** the target production rate is about **ν = 0.1 Hz**
- **FST layering is the most inexpensive technology** (< 30 cents per 1 target)

# BACKGROUND:
# Cryogenic layering in the moving free-standing targets (FST technology)

## Initial cryogenic target with liquid $D_2$ fuel

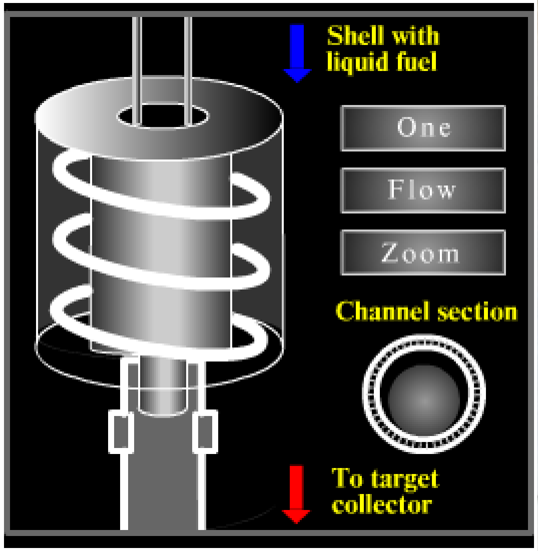


## Finished cryogenic target with solid $D_2$ layer



CH shell: ∅ 1.23 mm
Layer: 41 um, $D_2$+20% Ne
Nu < 2%, $\delta$ < 0.5 um

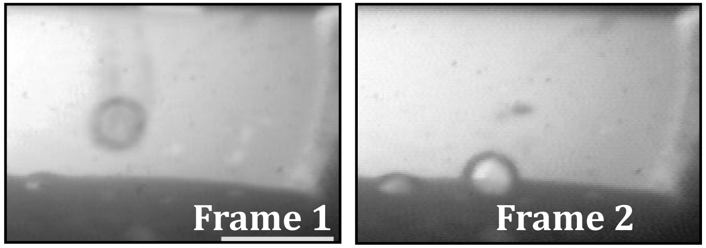
## FST-layering module
### general view & physical layout




## Cryogenic experiment

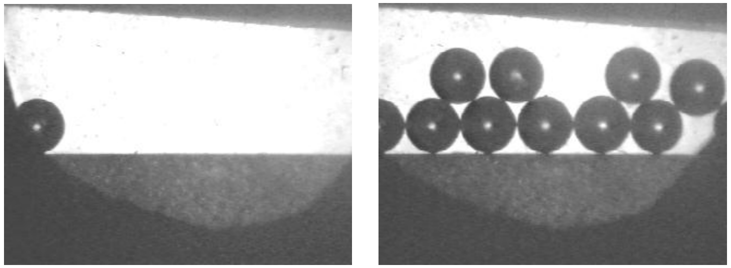
I.Osipov, A.Kupriyashin, E.Koshelev

## Cryogenic target injection into the test chamber at 5 K




Target in free-fall    Target landing

## Rep-rated injection of 1 mm targets at 5 K, f = 0.1Hz (batch mode)



t = 0    t = 100 s

# The FST technology is unique and there is not alternative of that kind

- **FST principle:**

  - Targets are moving and free-standing (unmounted)

  - Target injection between  the basic units of  the CTF

  - Time & space minimization for all production steps

- **FST result:**

  A batch mode is applied, and high cooling rates are maintained (1-50 K/s) to form isotropic  ultra-fine solid layers inside free-rolling targets

- **FST status:**

  FST technology and facilities created on its base are protected by the RF Patent and 3 Invention Certificates

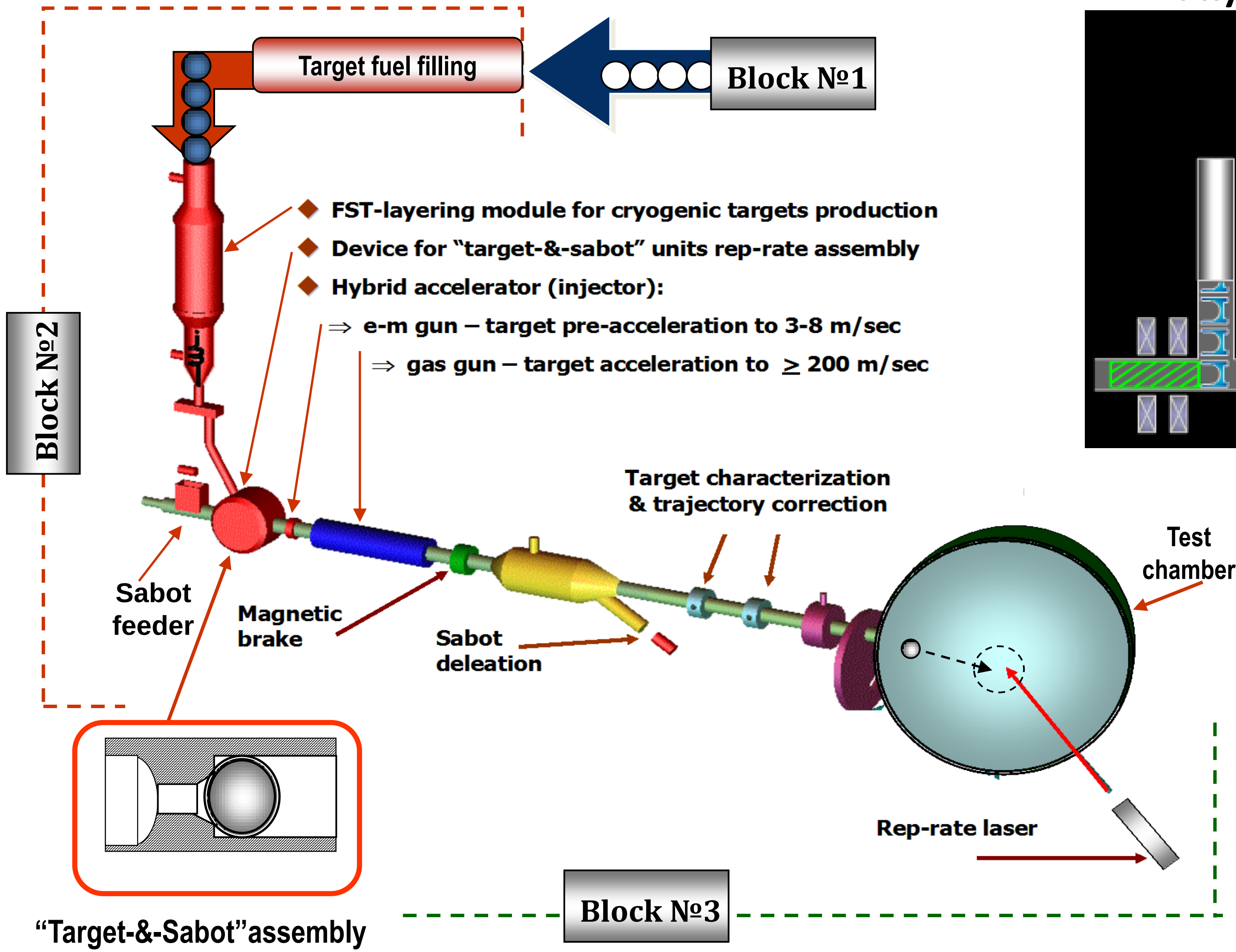




**NEXT STEP: FST technology demonstration for cryogenic targets of  a reactor scale with rep-rate production up to ~1 Hz and more**

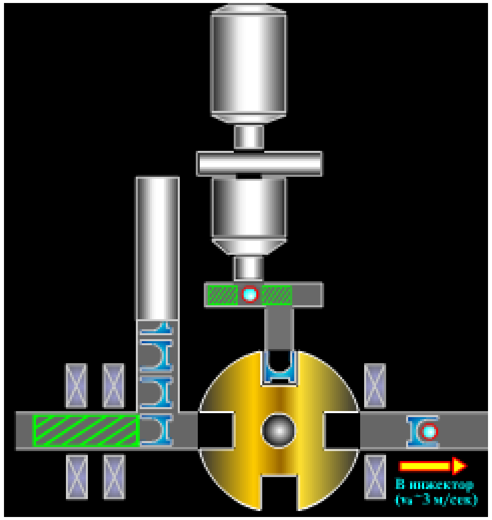
Reactor-scale targets: CH shells  ∅2-4 mm, layer thickness ~200-300 um

# CRYOGENIC TARGET FACTORY: Concept for continuous production & high-rep-rate target transport to IFE reactor




"Target-&-Sabot"assembly

## Physical Layout



**Block №1**
**Reactor shells,**
∅ 2 ÷ 4 mm
**Block №2**
**Cryogenic targets production & assembly,** D2-layer ~200÷300 um-thick
**Block №3**
**Cryogenic injector,**
V ≥ 200 m/s,
ν ≥ 1Hz, T~17-18 K

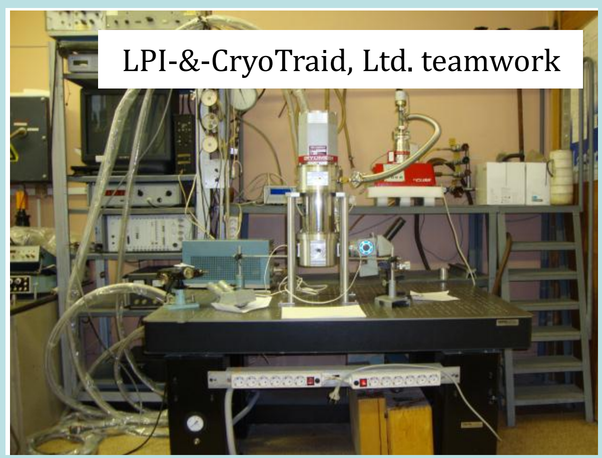
# Basic elements of CTF have been tested by LPI on the prototypical models. That allows risk minimization at the CTF construction & start-up.

**Cryogenic targets:**
**FST** method for fuel layering inside free-rolling targets

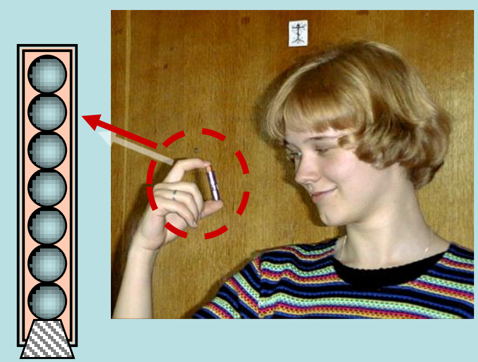

**Startup of the FST facility at the LPI in 1999**

**Fill System:**
Filling of CH shells with gaseous fuel up to 1000 atm at 300K

**Cryogenic target characterization:**
100-projections visual-light tomograph with 1 um space-resolution



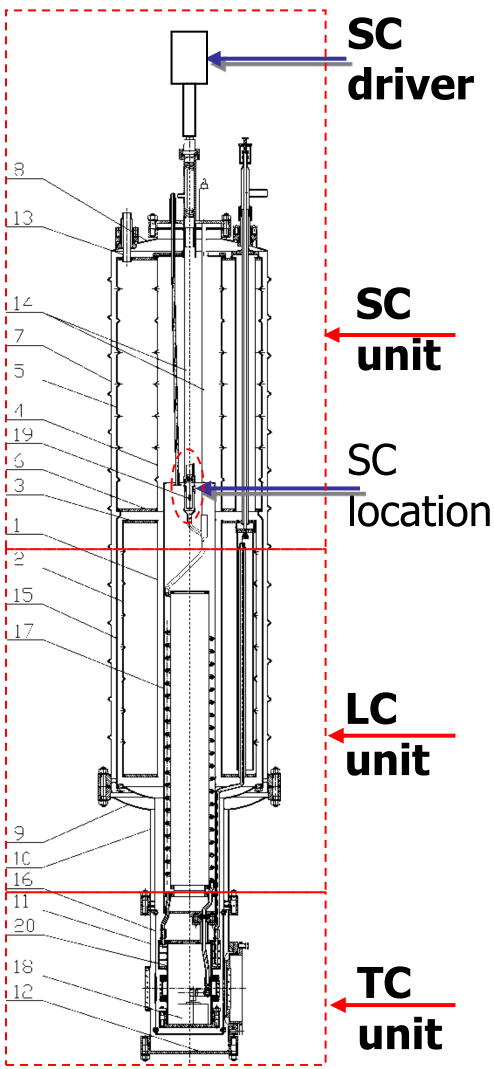

**Maglev transport systems:**
Facility for research in the area of HTSC levitation at T $\leq$ 18 K



**Handheld Target Container**
for fuel filled shells transport at 300 K from the fill system to the FST-layering module

# FST-layering module (1 Hz operation in a batch mode) designed by LPI for EU project "HiPER" can serve as a prototype for CTF

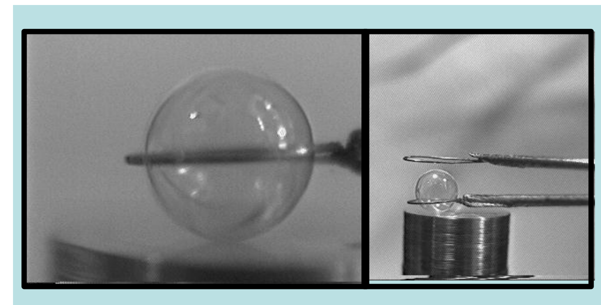
- **Drawing of the FST-layering module for HiPER project**




- **Mock-ups for testing the operational parameters**

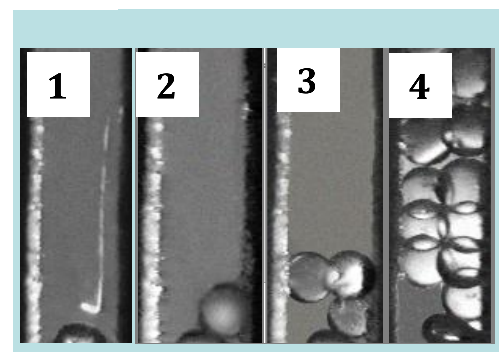
A set of the FST-layering channels (LC)

Shell container (SC)



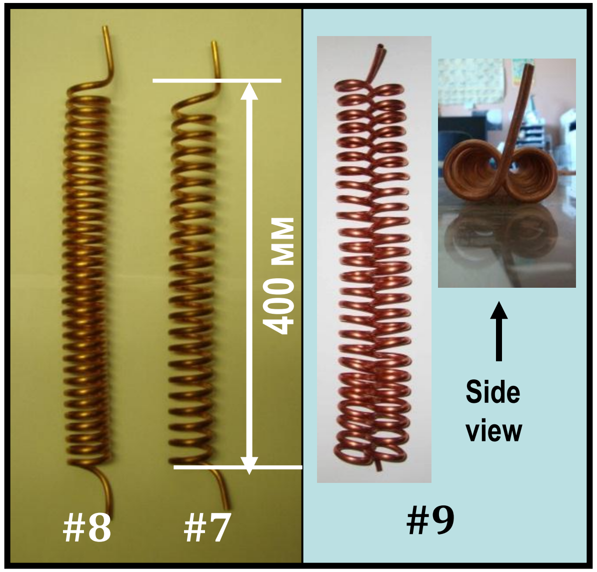
Positioning device
with the ring manipulator

Optical test chamber (TC)



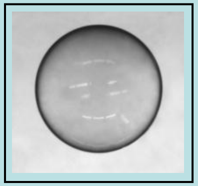

Target collector: demonstration
of targets gravity injection

# Recent results: a double-spiral FST-layering channel (LC) is the best prospect for reactor targets production

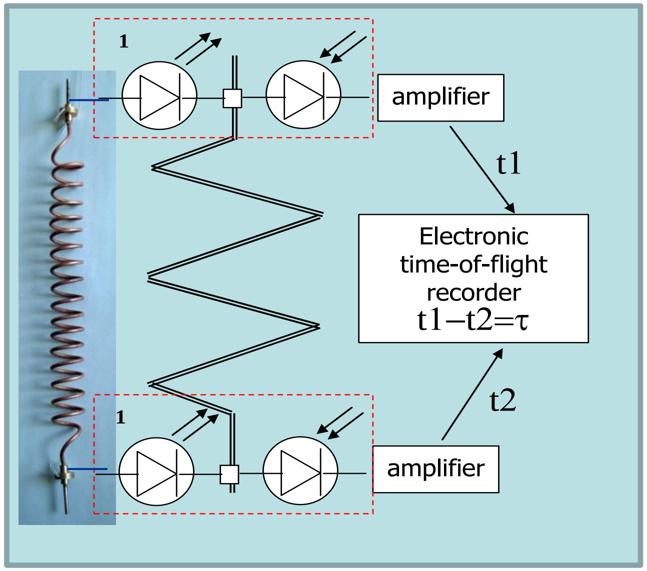



**Mockups of the spiral LC**
#7, #8 ⇒ single-spiral LC (**SSLC**),
#9 ⇒ double-spiral LC (**DSLC**),
Cupper tube OD=38mm

**HiPER target**
CH shell: ∅2 mm x 3 um
DT-layer: 211 um-thick



**CH shells of ∅ 2mm**
for mockups testing.
Supplied by the STFC, UK




**Schematics of measuring the time**
of target movement inside the LC
1 – optronic pair made from IR-diodes

## Time of target movement inside the mockups

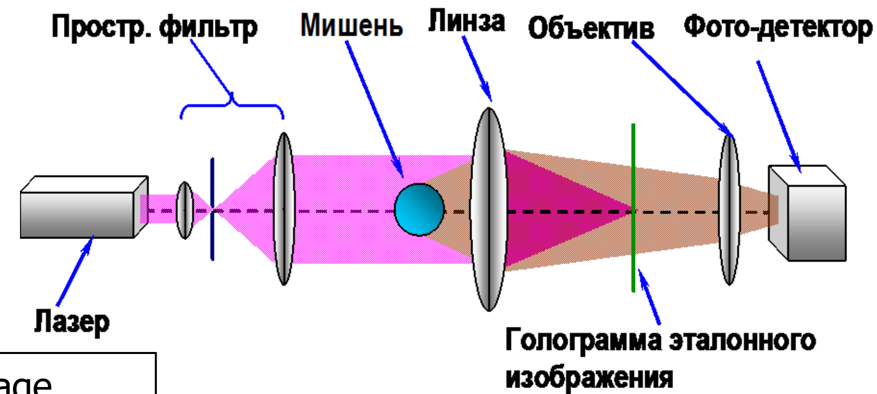
(testing results at 300K, data averaged for 10 shots)

**SSLC**
**#7: $t_m$= 9.8 s #8: $t_m$= 16.4 s**

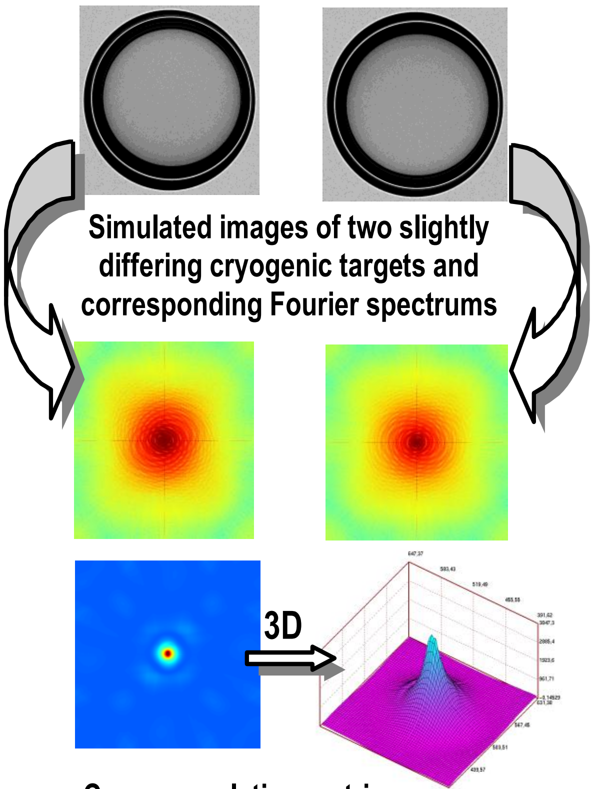
**DSLC**
**#9: $t_m$= 23.5 s**

**Calculations**
FST-layering time for HiPER targets
**$t_l$ ~ 10 -to- 15 s**

# Fourier holography of image recognition is a promising way for on-line characterization of a flying target (IAEA TC # 13871)

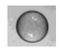


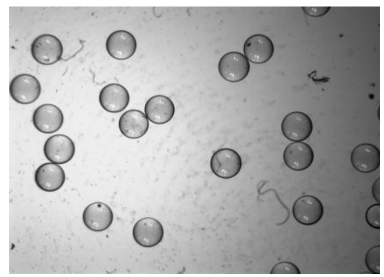

- The recognition signal is maximal in the case of good conformity between the real & etalon images
- The operation rate of such a scheme is several usec



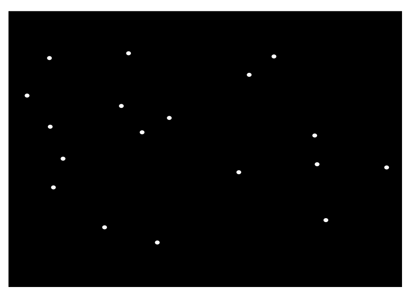

Simulated images of two slightly differing cryogenic targets and corresponding Fourier spectrums

Cross-correlation matrix of the images

 ← Etalon image



Studied image of the shells batch



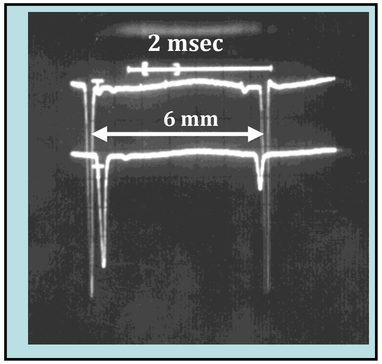
Cross-correlation matrix of the studied and etalon images

Computer experiments have shown that this approach allow

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

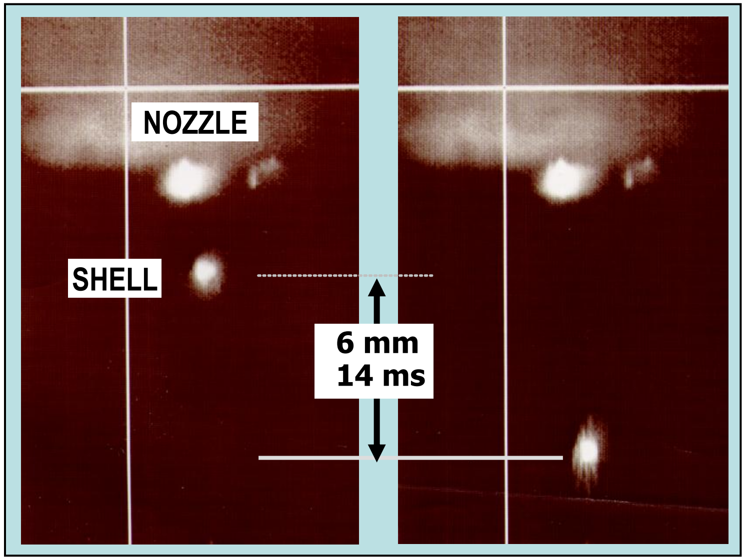
# Target injection under gravity: prototyping a gravity assembly of "Target-&-Sabot" (T<18K) and refining a trajectory control of flying shells

**Gravity injector test stend**
developed by the Lebedev Physical Institute
and the Rutherford Appleton Lab.
(1989-1991)



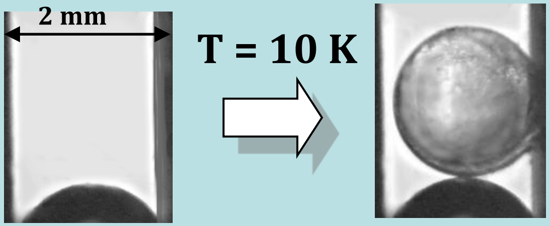

**Double-beam oscilloscope data of the injected shells**

**High-speed video filming**
of injected shell into the test chamber;
Video-camera *KODAK ECTAPRO 1000 IMAGER*

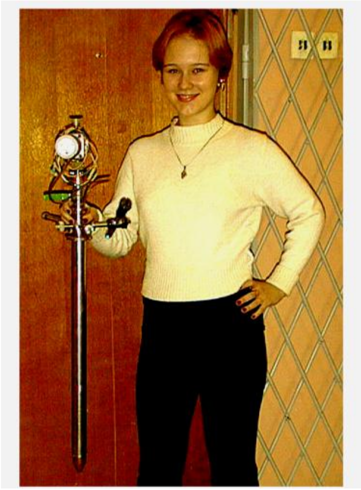



**Refining on-line control of trajectory of the flying shells**

**Prototyping a gravity assembly of "Target-&-Sabot" at T = 10 K**




Gravity delivery of cryogenic target
from the FST-layering channel
into a cylindrical cavity



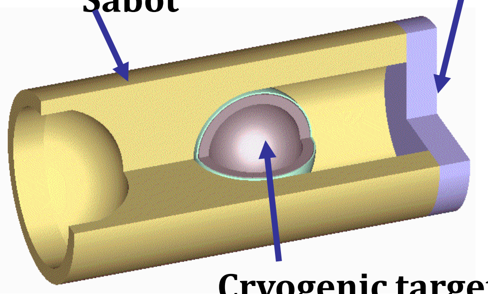
**Prototype of a gravity injector**
integrated with
the FST- layering channel

**Data for 50 shots**

(for CH shells of ∅ ~ 1 mm)

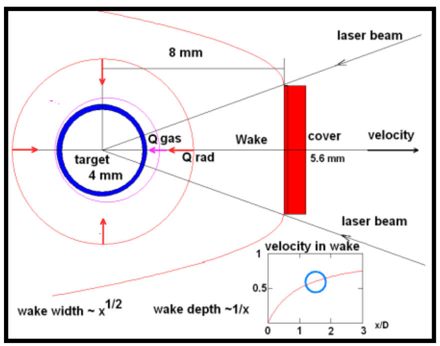
1. **Trajectory angular spread** **≤ 3 mrad**
2. **Injection velocity** **0.43 ÷ 0.55 m/s**

# RESUME on the MULTIPLE TARGET PROTECTION METHODS
## Outer protective cryogenic layer, reflective coating, protective cover, sabot




### TARGET ACCELERATION INSIDE INJECTOR

Special sabot is used for
- transfer a motion pulse onto a target
- target protecting from g- & heat- load arising during target acceleration

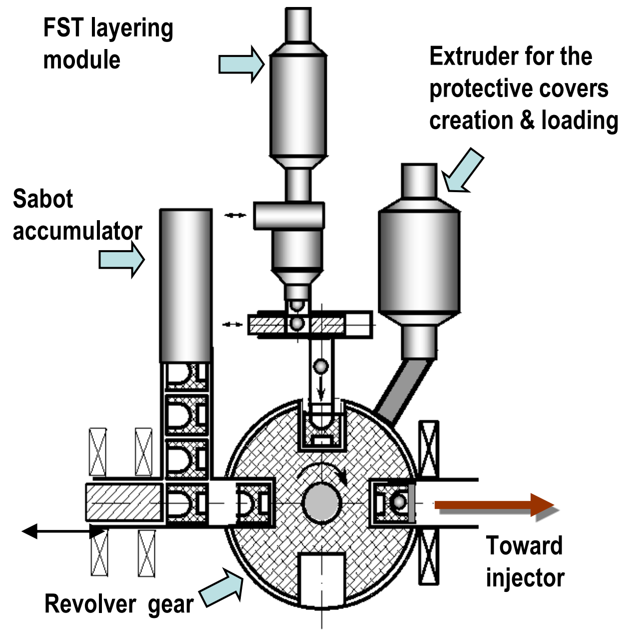


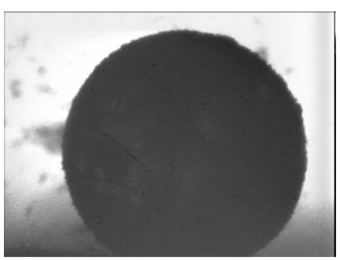

### TARGET FLIGHT INSIDE REACTION CHAMBER

PROTECTIVE COVER forms a wake area in the fill gas to protect target from the head wind and to avoid convective heating.

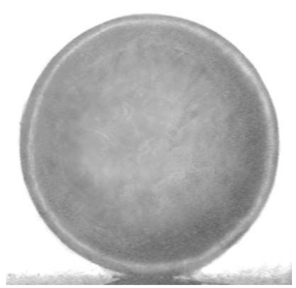
Protective cover material: solid D2, Ne or Xe

### Cryogenic Target Factory with the device for high-rep-rate assembly of "sabot-&-target-&-cover" units



1. Target with outer protective cryogenic layer



2. Cryo target with outer reflective layer from Pt/Pd (200 Å-thick)

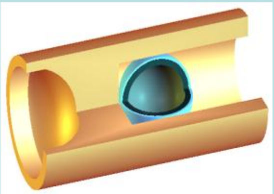
### TARGET ACCELERATION & FLIGHT

**1. Outer protective cryogenic layer:** Technology of deposition on the shell the outer layer from solid D2, Xe or Ne to protect target from overheat during its flight (technology developed at LPI)

**2. Outer reflecting metal layer** (technology developed at LPI)

# Acceleration stage ⇒ after FST layering, the targets are loaded into sabots. Resent results: sabot material study to enhance the efficiency of the electromagnetic (e-m) injector

**(1) SFM sabot:** Bulk **S**oft **F**erro **M**agnetic (like annealed iron)




- **Numerical study:**

  **SFM sabot can be used at T< 20 K**

- **Successful experiments:**

  **SFM sabot acceleration were carried out at T = 5-to-80 K**

**(2) MD sabot :** **M**agneto-**d**ielectric (soft ferromagnetic particles distributed over a polymer matrix)

- **Numerical simulations:**

  **MD sabot can be used more effectively than SFM sabot**

- **Experimentally, the next R&D steps will be required**

**↓ NEW RESULTS ↓**

**(3) HTSC or maglev sabot:** **H**igh-**T**emperature **S**uper**c**onductor

- **LPI has proposed**

  **using HTSC materials for development of maglev technology for target handling & transfer**

- **LPI made**

  **HTSC ceramics $YBa_2Cu_3O_{7-X}$ (Tc~91K, Bc~5.7T at 0K) using method of solid phase reactions**

- **POP experiments:**

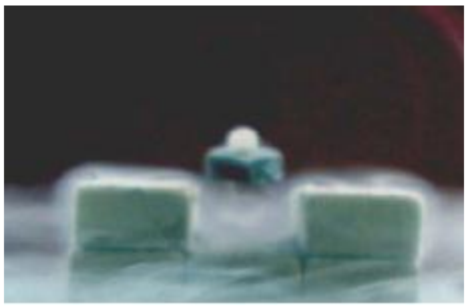
  **stable levitation & transfer of different HTSC samples at T = 6-to-80 K**

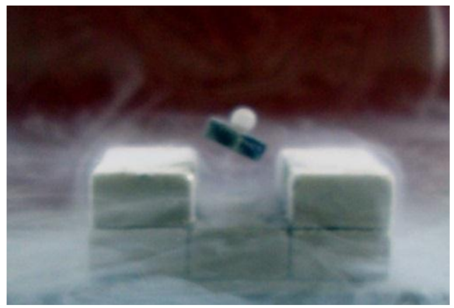
# Set #1: experiments at T ~ 80 K ($LN_2$) have demonstrated stable levitation of the HTSC samples of different geometry

**❑ Levitation of the HTSC platform with CH shell on it**

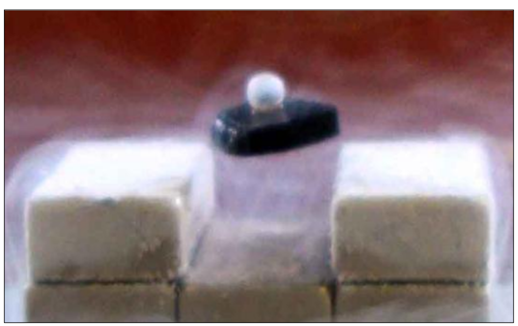
HTSC sample size: 8 x 8 x 6 mm; Magnet: SmCo, B = 0.4 T

CH shell size: ∅ 2 mm



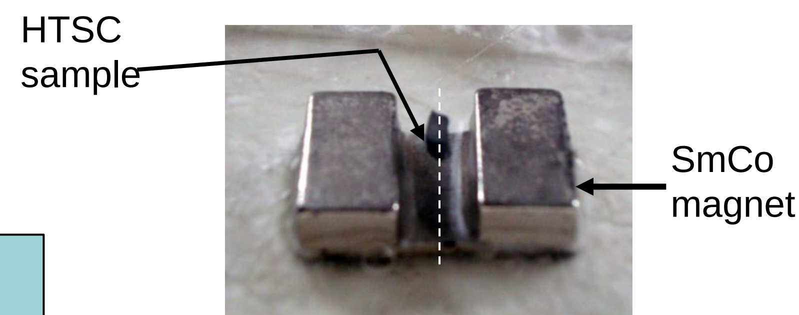


**HTSC experiments at T ~ 80K**



**❑ HTSC sample aligns with the line of minimal magnetic induction**

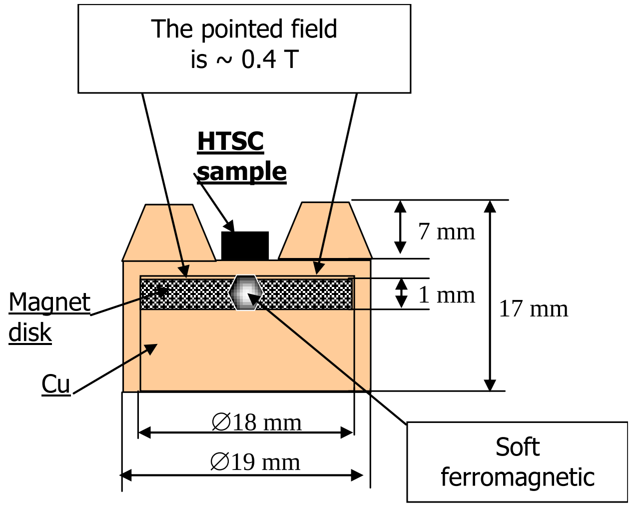
Sample size: 8 x 2 x 2 mm;  Magnet: SmCo, B = 0.4 T




**HTSC samples made at LPI**

**- material:** superconducting ceramics $\mathbf{YBa_2Cu_3O_{7-x}}$

# Set #2: experiments at T = 6-to-18 K have confirmed the possibility of using HTSC as a driving body for cryogenic target transfer

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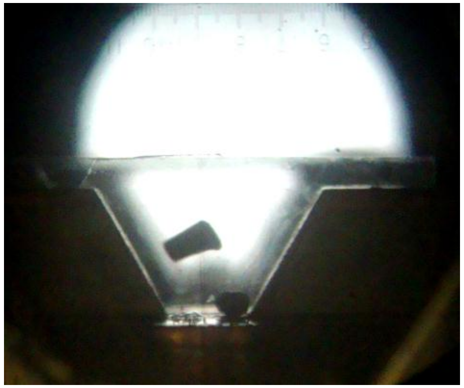
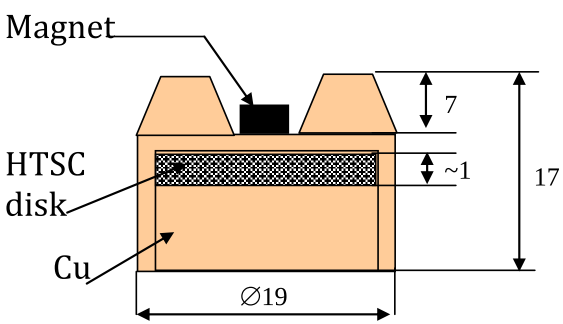
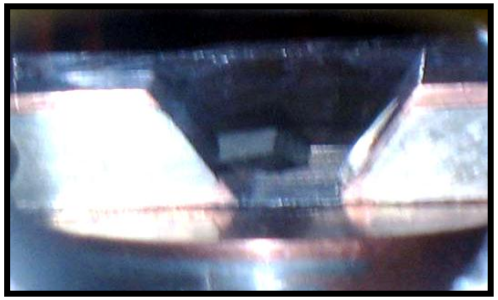


**HTSC- sample levitation over a magnet, T=18 K**




B



**Schematics of the experiments (2)**

**Magnet levitation over the HTSC sample, T = 6 K**

- **Comparative experiments demonstrated stable levitation of the HTSC samples in the range of 80 -to- 6 K**
- **Resume: for reduction in cost, model experiments can be carried out at T ~ 80K** (liquid nitrogen temperatures)

# POP experiments (~ 80K): non-contact positioning & frictionless transport of the HTSC projectile inside e-m injector

## ❑ Ordered motion of HTSC sample with CH shell over the PMG

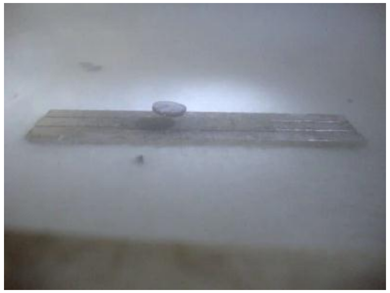
**PMG:**
4 permanent magnets
**Magnet**:
SrBa ferrite, 0.18 T
**Screw insert:**
soft ferromagnetic ARMCO
**CH shell**:
2-mm-diam

## ❑ Stable levitation of the YBaCuO sample in the field of permanent magnet

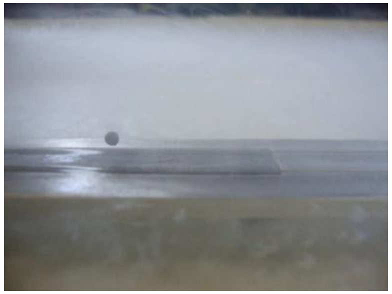
**Magnet** (commercial):
Ferrite F8
B~0.16 T
OD 15 mm
ID 9 mm
5-mm-thick
**Sample** (made at LPI):
YBaCuO ceramics
Size ~ 2mm

## ❑ Maglev braking of lateral motion of the HTSC projectile

The PMG made from a soft ferromagnetic plate mounted onto the permanent magnet from NdFeB (B = 0.4 T)



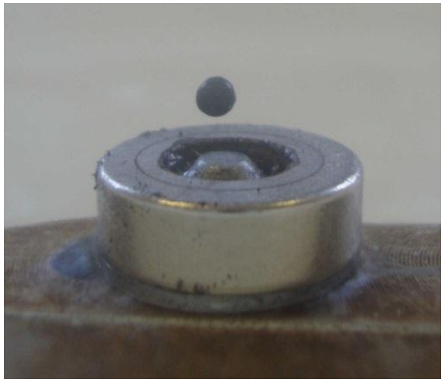
HTSC pellet ∅ 12.4 mm



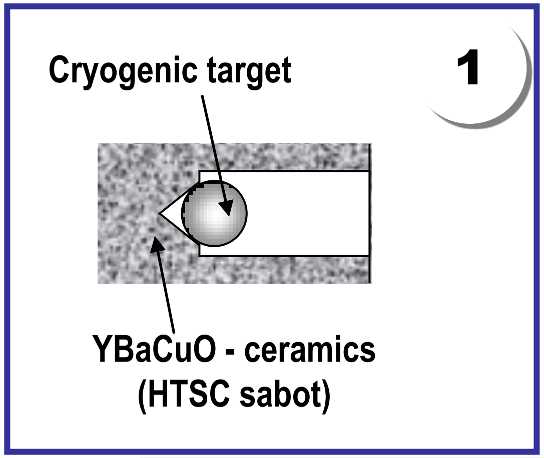
HTSC coated CH shell ∅ 2mm

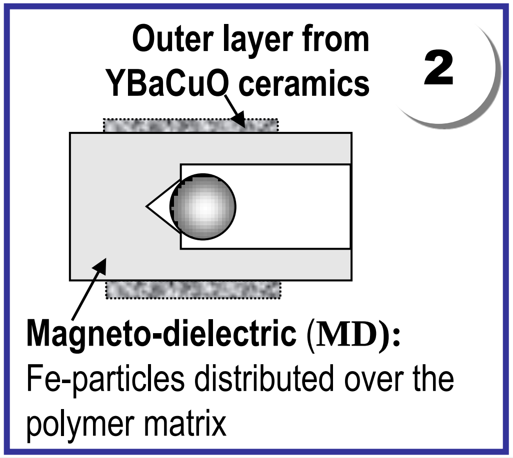
## ❑ Stable levitation of the CH shell with the outer YBaCuO layer

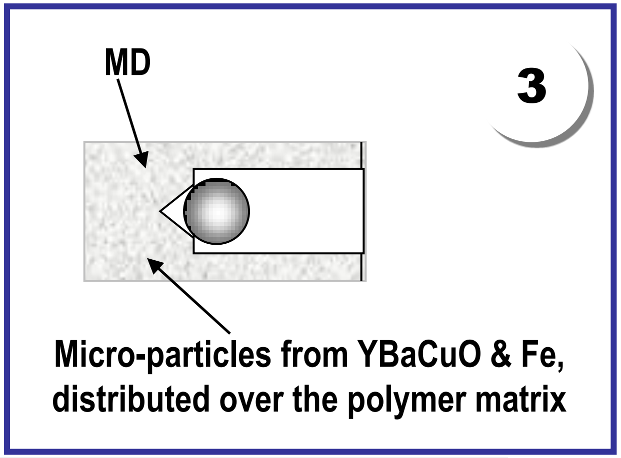
**Magnet**: ferrite F8,
B~0.2 T,
OD 14-mm,
4-mm-thick
**CH shell**:
2-mm-diam
**YBaCuO layer:**
~10-um-thick



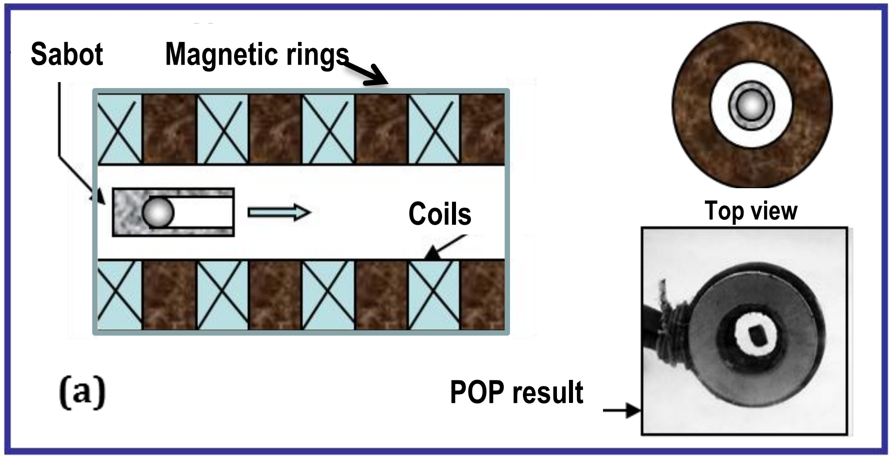
# Different designs of a maglev sabot based on using superconducting ceramics YBaCuO

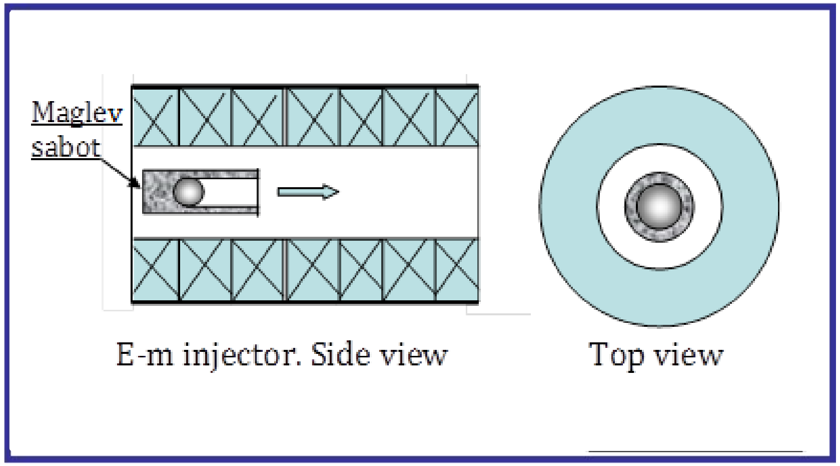



**Sabots for almost frictionless motion inside the electromagnetic injector, which enhance the operating efficiency of the maglev accelerator**




**E-m injector + HTSC projectile. A design options with the HTSC sabot**

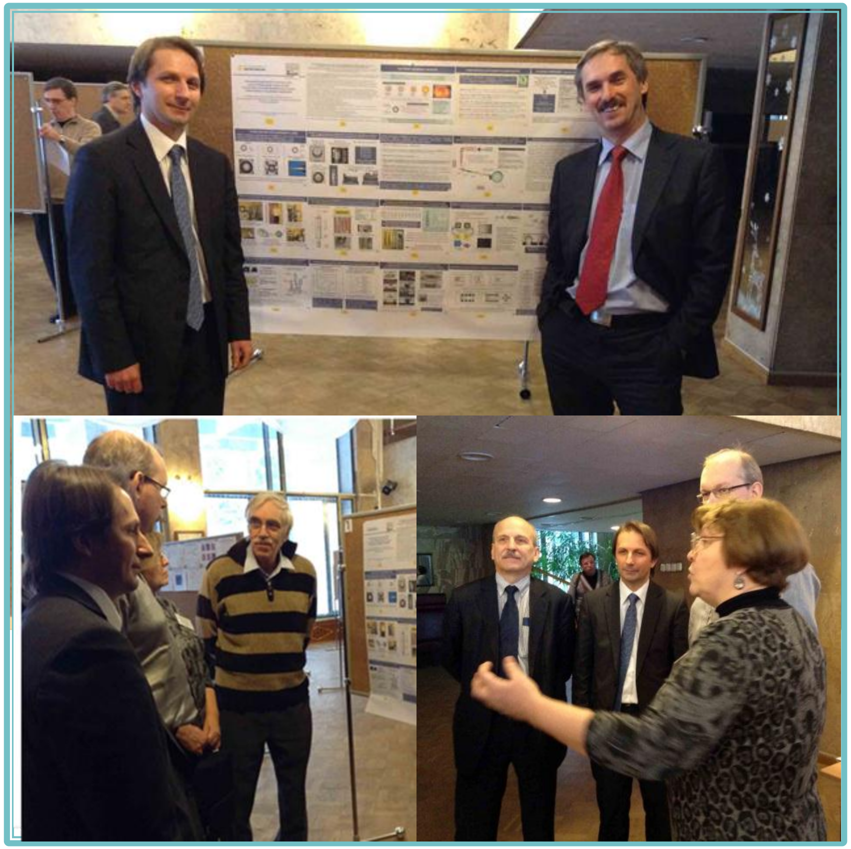
# We are going to realize the CTF concept based on FST in the next generation project

- **Project Title:**
  **FST transmission line for IFE: high-rep-rate target fabrication, injection and tracking**

- **Project goal:**
  **- Refining the FST- technology for producing the reactor scale targets**
  (Ø=2-4 mm, cryogenic layer W=200-300um)
  **- Creation of FST transmission line for IFE and demonstration of its 1-Hz operation**

- **Presented:**
  **40th International conf. on Plasma Physics & Controlled Fusion (Feb. 10–14, 2014, Russia)**
  by I.V.Aleksandrova, E.R.Koresheva, E.L.Koshelev, B.V.Kuteev, A.I.Nikitenko, V.N.Nikolaev, I.E.Osipov

- **The project is under consideration**



Project participants at 40th International conference on Plasma Physics and Controlled Fusion, February 10–14, 2014 (Zvenigorod, Russia)

# Summary results for the activity of Russian Federation* in the area of “Cryogenic Targets Factory for IFE”

*/**Lebedev Physical Institute of Russian Academy of Sciences**
in collaboration with other Russian organizations, such as

- Federal State Unitary Enterprise “Red Star”
- National Research Center “Kurchatov Institute”
- Power Efficiency Center INTER RAO UES
- Moscow State University
- CryoTrade, Ltd.

and under financial support of Russian Foundation of Basic Research, International Science & Technology Center, International Atomic Energy Agency, EU project HiPER

Presented at 25$^{th}$ IAEA FEC by **Elena Koresheva** (Lebedev Phys. Inst.)

# Cryogenic Target Factory for IFE: summary

- **FST technology has been developed at LPI**, which forms an isotropic ultrafine fuel layer inside moving free-standing targets

- Our studies show that **application of isotropic ultrafine fuel layer makes risk of the layer destruction minimal** during target delivery

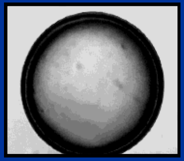
- **A full scaled scenario of the FST transmission line operation has been demonstrated for targets under ∅ 2 mm**, namely:

  ⇒ Fueling a batch of free-standing targets (up to 1000 atm $D_2$ at 300 K),
  ⇒ Fuel layering inside moving free-standing targets using FST technology: cryogenic layer up to 100 um-thick,
  ⇒ Target injection into the test chamber with a rate of 0.1 Hz
  ⇒ Target tracking using the Fourier holography approach (computer expts)

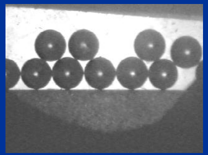
- **Free-standing target positioning & transport using the quantum levitation effect** of the high temperature superconductors (HTSC) have been proposed. POP experiments have proved the efficiency of this approach **(result 2012-2014)**

- **A prototypical FST layering module for rep-rate production of reactor-scaled cryogenic targets has been designed** based on the results of calculations and mockups testing **(result 2012-2014)**

- **LPI continue developing the of R&D program on CTF** in collaboration with Power Efficiency Center of INTERRAO UES & National Research Center "Kurchatov Institute". **New generation project is under consideration.**

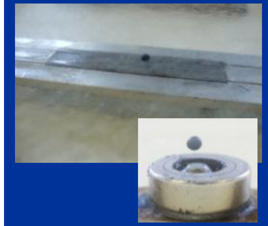


Cryo target with ultrafine fuel layer (∅1.5mm)



Targets rep-rate injection under gravity: 0.1Hz, 5K

Cryogenic gravity injector



HTSC maglev for target positioning & transport