CONCEPTION of a CRYOGENIC TARGET FACTORY for IFE

Elena Koresheva, **Lebedev Phys. Inst. of RAS**

Irina Aleksandrova, Eugenie Koshelev, Andrei Nikitenko,

Boris Kuteev,

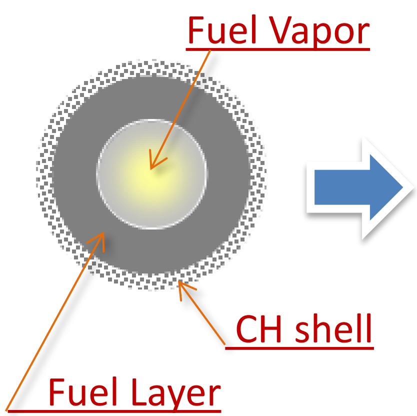
Vladimir Nikolaev, Igor Osipov

25th IAEA Fusion Energy Conference, St. Petersburg, October 13-18, 2014

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

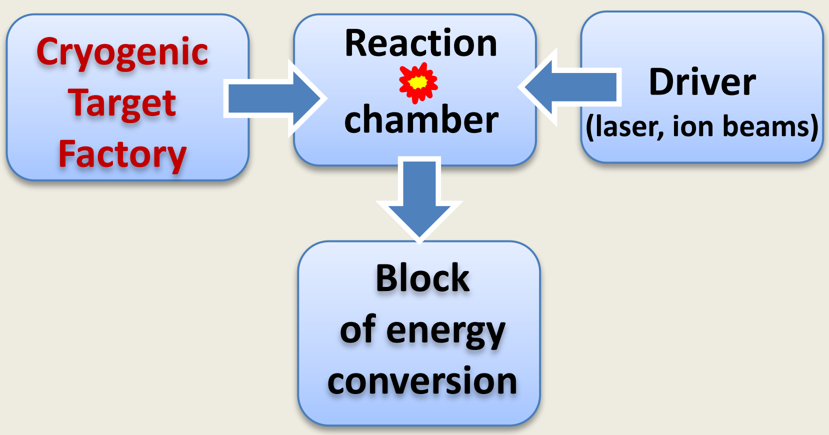
Direct-drive Cryogenic Fuel Target



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

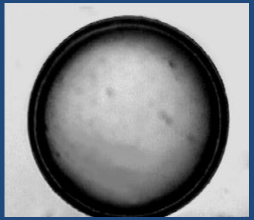
The CTF is based on the approaches proposed & examined at LPI [1]:

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

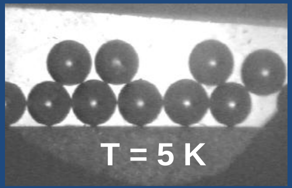
(b) Magnetic levitation (maglev) transport systems for almost frictionless motion of the cryogenic targets at their handling [3]

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

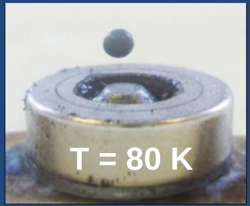
The POP and computer experiments have proved the interaction efficiency of the proposed approaches



FST –layering : free-standing cryo target



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



HTSC coated CH shell levitating above magnet

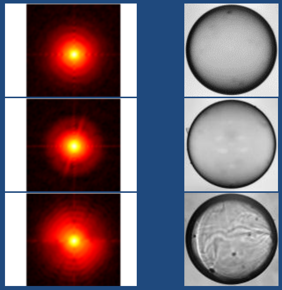


Image Fourier trans-forms of the shells with different imperfections

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

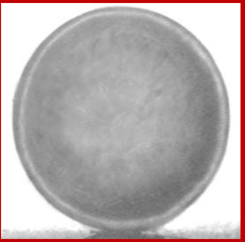
CTF prototype created and tested at LPI for targets under 2 mm-diam: CURRENT PARAMETERS

- **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

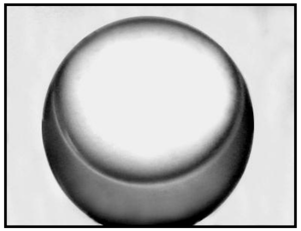
– Minimal layering time: **t_f < 15 sec** (conventional production methods: **t_f ~ 24 hrs**)

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

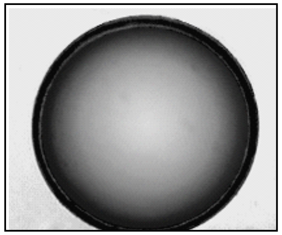
- **Rep-rate mode of the CTF operation:** the target production rate is about **ν = 0.1 Hz**
- **FST layering is the most inexpensive technology** (< 30 cents per 1 target)

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

Initial cryogenic target with liquid D_2 fuel

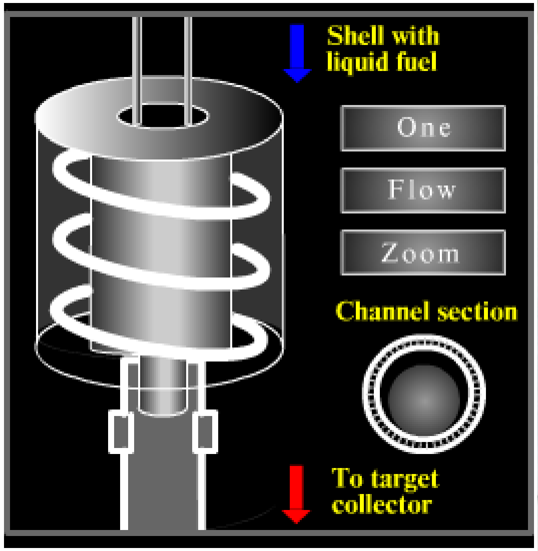


Finished cryogenic target with solid D_2 layer



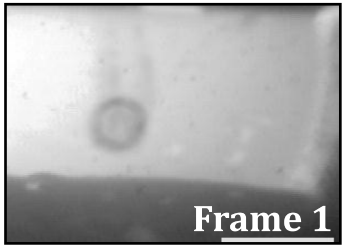
CH shell: ∅ 1.23 mm
Layer: 41 um, D_2+20% Ne
Nu < 2%, δ < 0.5 um

FST-layering module
general view & physical layout

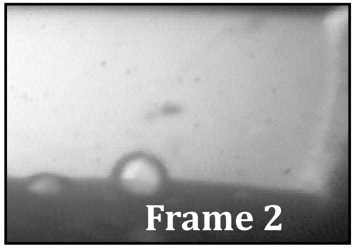


Cryogenic experiment
I.Osipov, A.Kupriyashin, E.Koshelev

Cryogenic target injection into the test chamber at 5 K

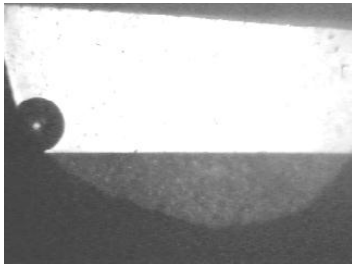


Target in free-fall

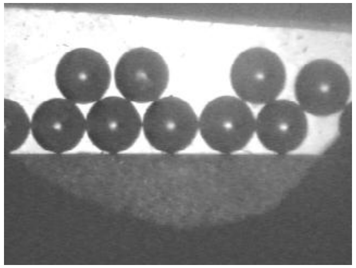


Target landing

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

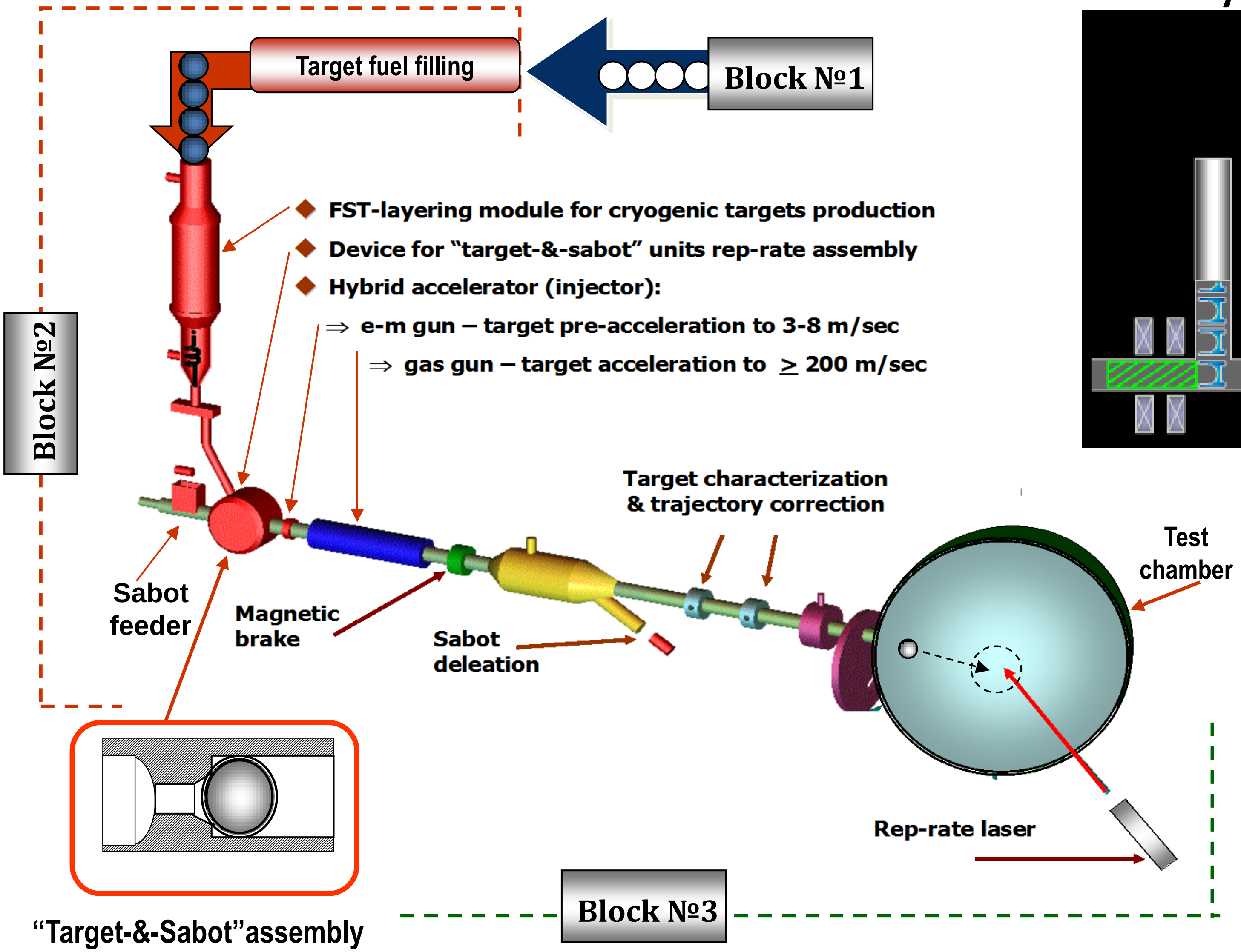
- **FST status:**

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

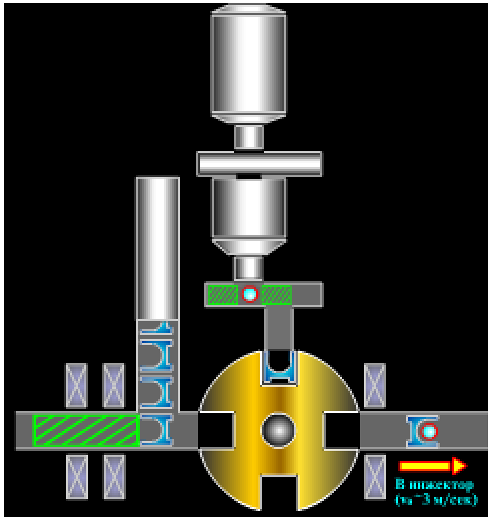
NEXT STEP: FST technology demonstration for cryogenic targets of a reactor scale with rep-rate production up to ~1 Hz and more

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



Physical Layout



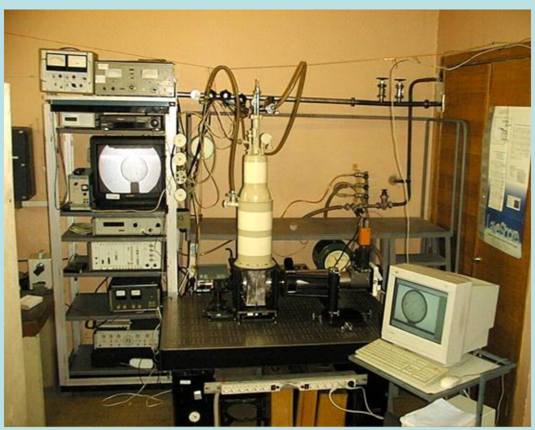
Block №1
Reactor shells,
∅ 2 ÷ 4 mm
Block №2
Cryogenic targets production & assembly, D2-layer ~200÷300 um-thick
Block №3
Cryogenic injector,
V ≥ 200 m/s,
ν ≥ 1Hz, T~17-18 K

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

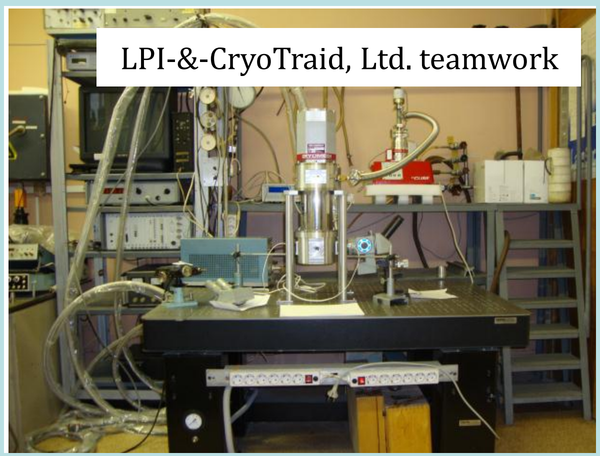
Cryogenic targets:
FST method for fuel layering inside free-rolling targets

Startup of the FST facility at the LPI in 1999

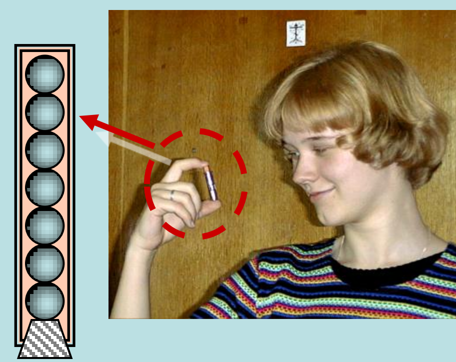
Fill System:
Filling of CH shells with gaseous fuel up to 1000 atm at 300K



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



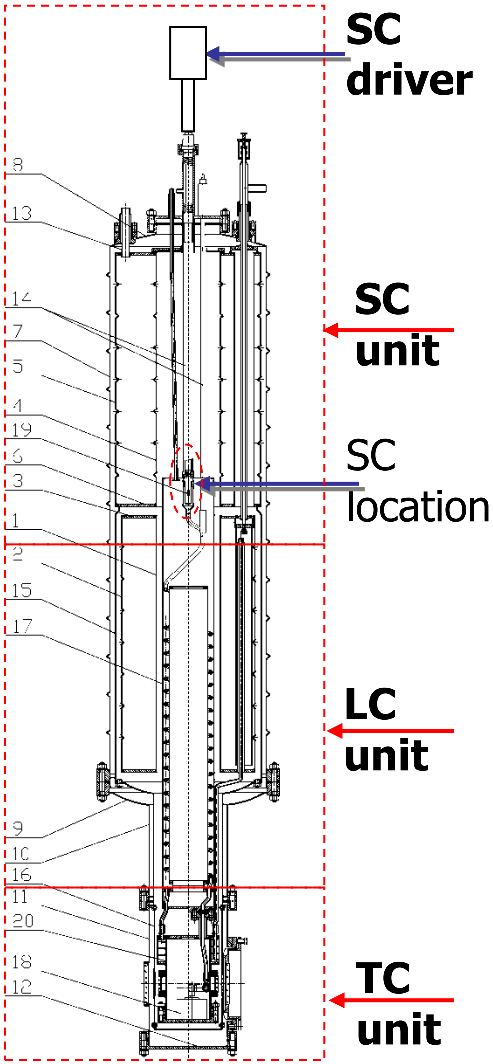
Maglev transport systems:
Facility for research in the area of HTSC levitation at $T \leq 18$ K



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

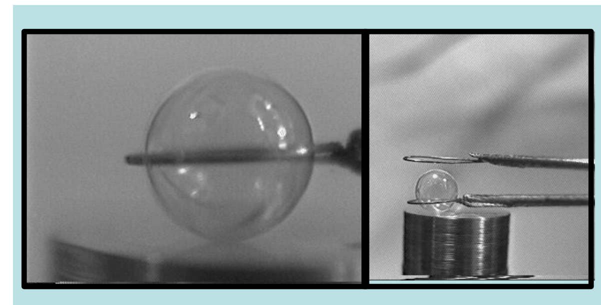
❑ **Drawing of the FST-layering module for HiPER project**



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

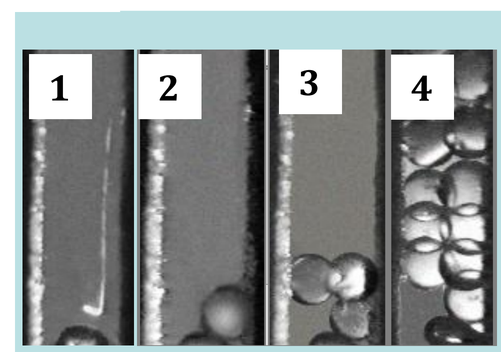
A set of the FST-layering channels (LC)

Shell container (SC)



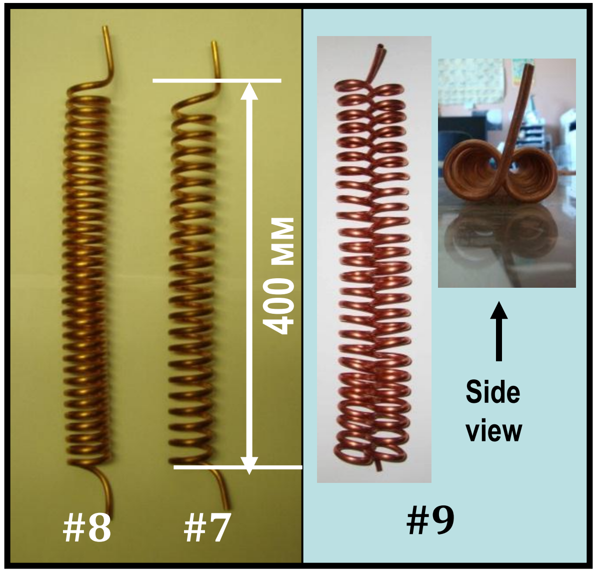
Positioning device with the ring manipulator

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

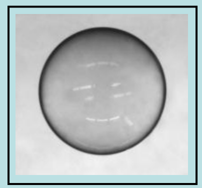


Mockups of the spiral LC

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

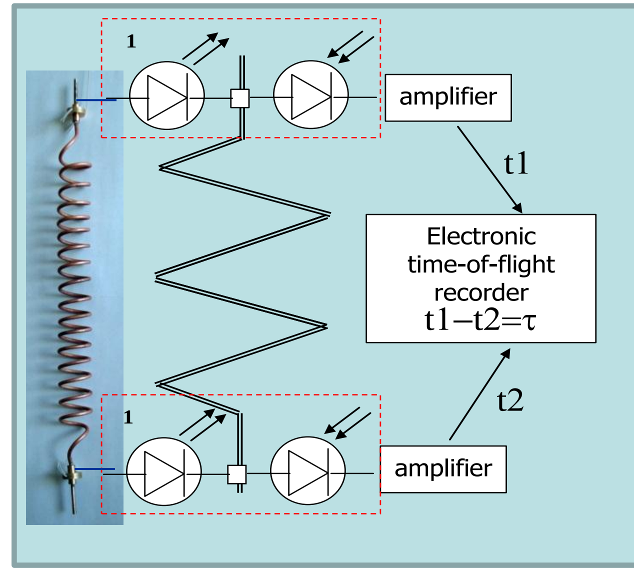
HiPER target

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	DSLC
#7: t_m= 9.8 s #8: t_m= 16.4 s	**#9: t_m= 23.5 s**

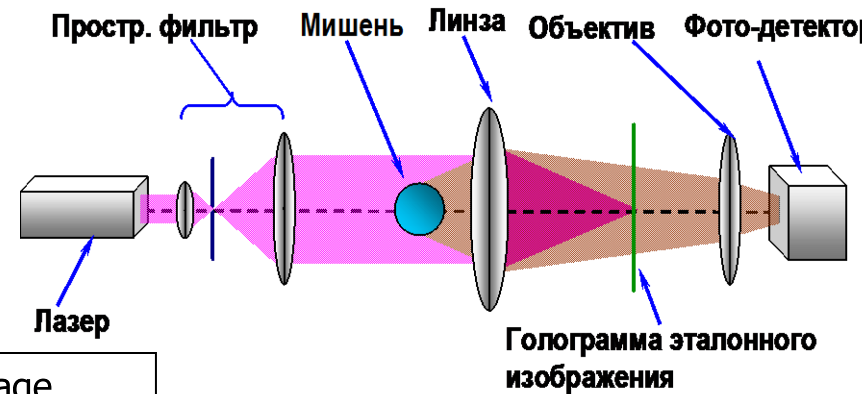
Calculations

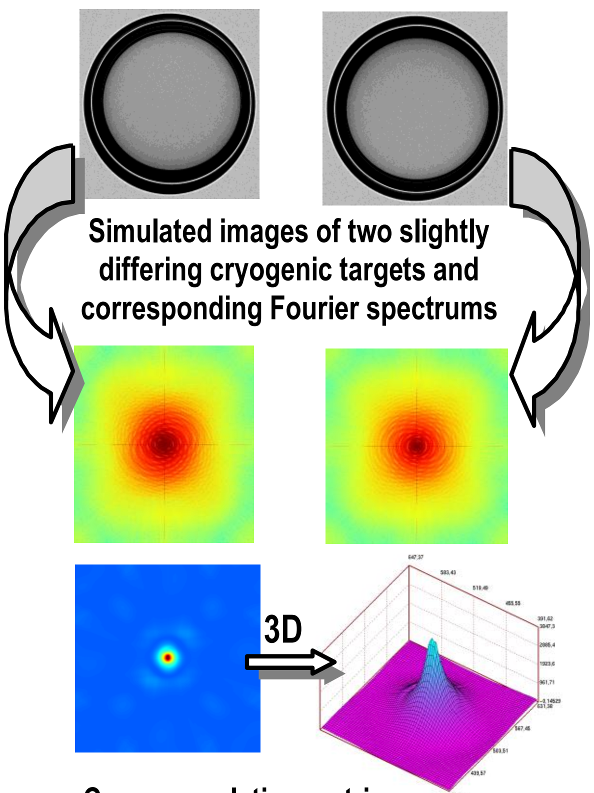
FST-layering time for HiPER targets

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)

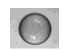
- The recognition signal is maximal in the case of good conformity between the real & etalon images
- The operation rate of such a scheme is several usec

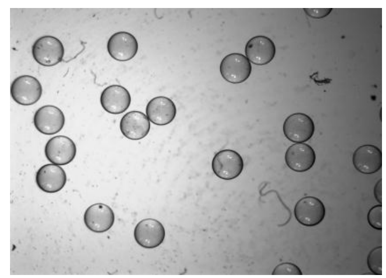




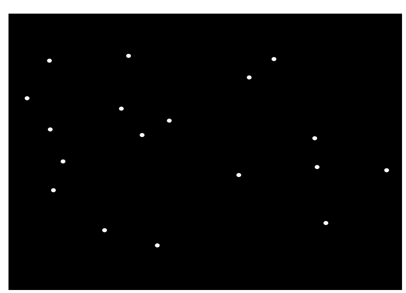
Simulated images of two slightly differing cryogenic targets and corresponding Fourier spectrums

Cross-correlation matrix of the images

 ← Etalon image



Studied image of the shells batch



Cross-correlation matrix of the studied and etalon images

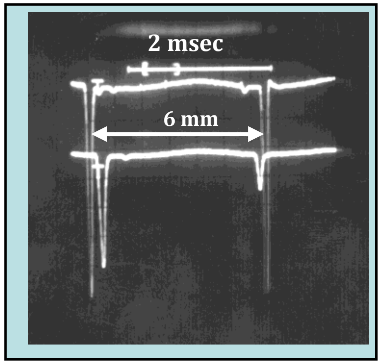
Computer experiments have shown that this approach allow

- 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

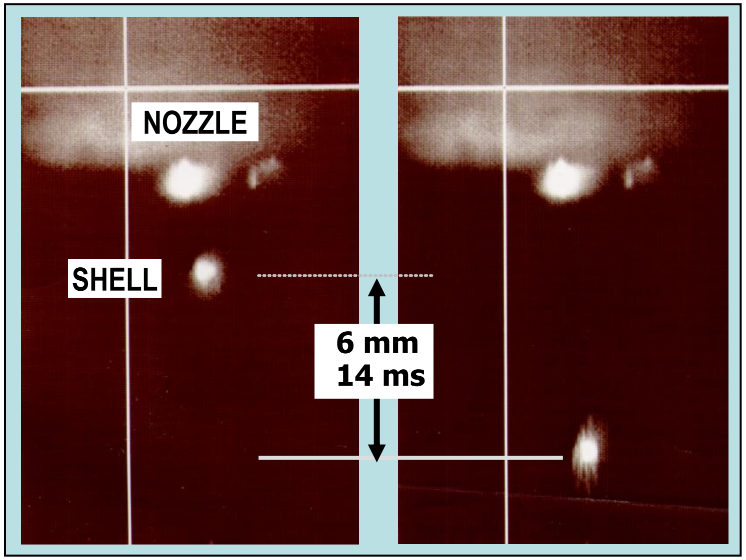
developed by the Lebedev Physical Institute and the Rutherford Appleton Lab. (1989-1991)



Double-beam oscilloscope data of the injected shells

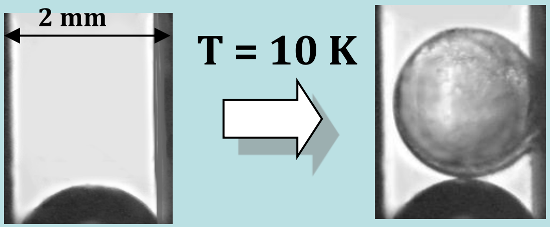
High-speed video filming

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

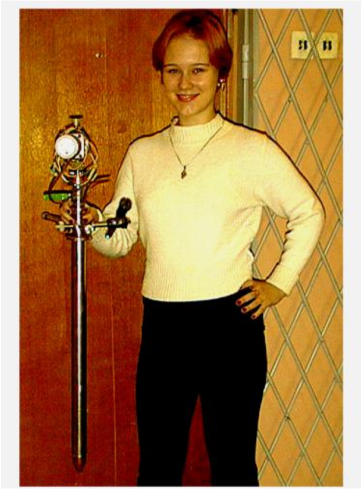


Refining on-line control of trajectory of the flying shells

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

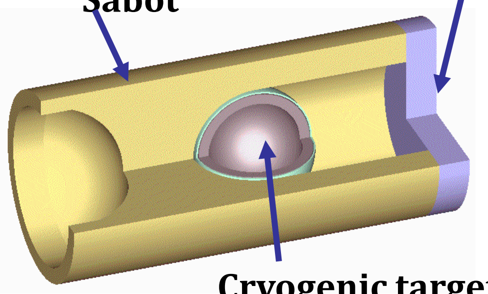
integrated with the FST- layering channel

Data for 50 shots

(for CH shells of ∅ ~ 1 mm)

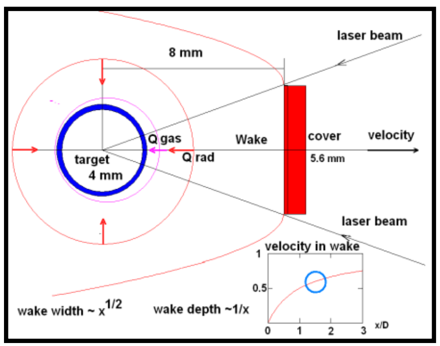
1. Trajectory angular spread	**≤ 3 mrad**
2. Injection velocity	**0.43 ÷ 0.55 m/s**

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

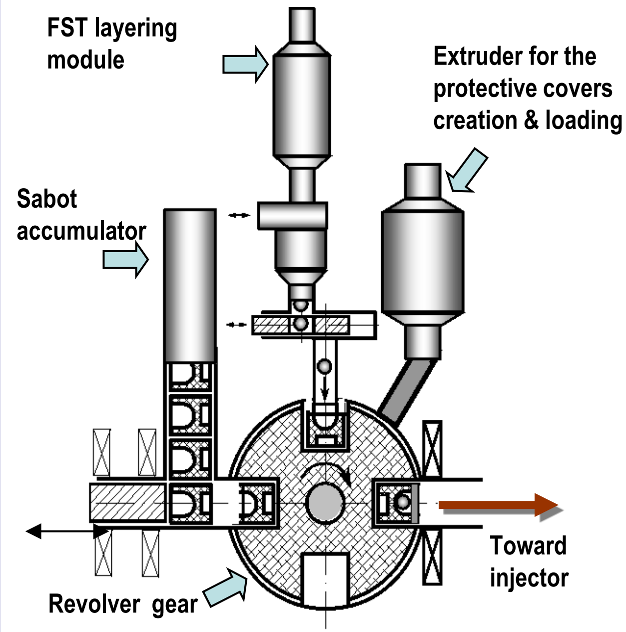


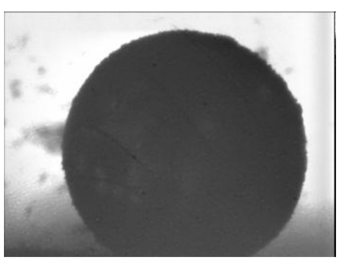
TARGET FLIGHT INSIDE REACTION CHAMBER

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

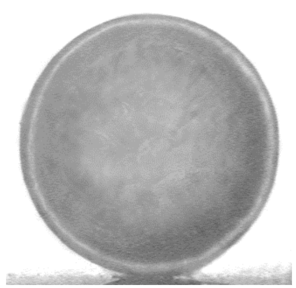
Protective cover material: solid D2, Ne or Xe

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

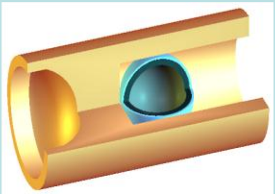
(1) SFM sabot: Bulk **S**oft **F**erro **M**agnetic (like annealed iron)

- **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



Target-&-Sabot assembly

T ~17- 18.5 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

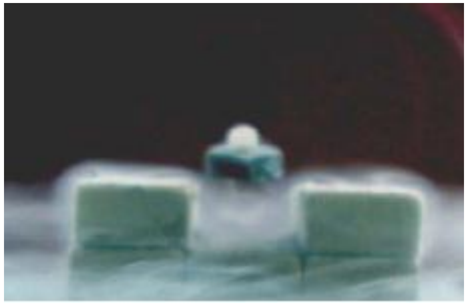
- **POP experiments:**

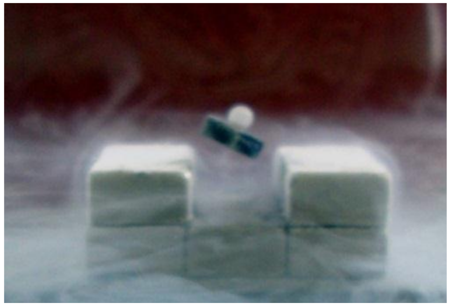
  stable levitation & transfer of different HTSC samples at T = 6-to-80 K

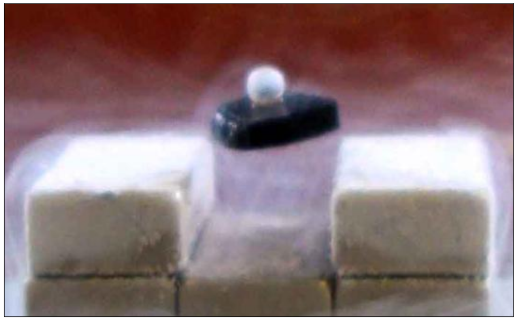
Set #1: experiments at T ~ 80 K (LN_2) have demonstrated stable levitation of the HTSC samples of different geometry

❑ 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



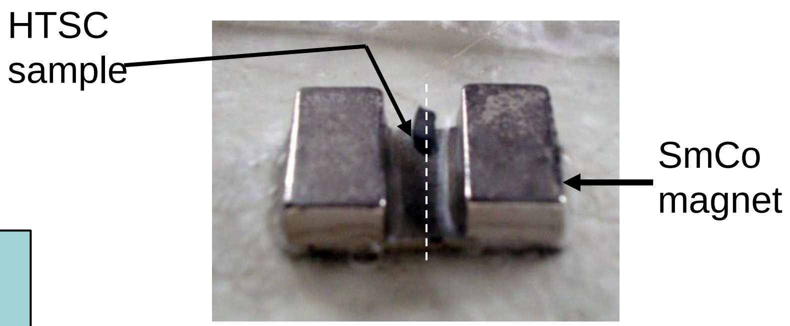




HTSC experiments at T ~ 80K

❑ HTSC sample aligns with the line of minimal magnetic induction

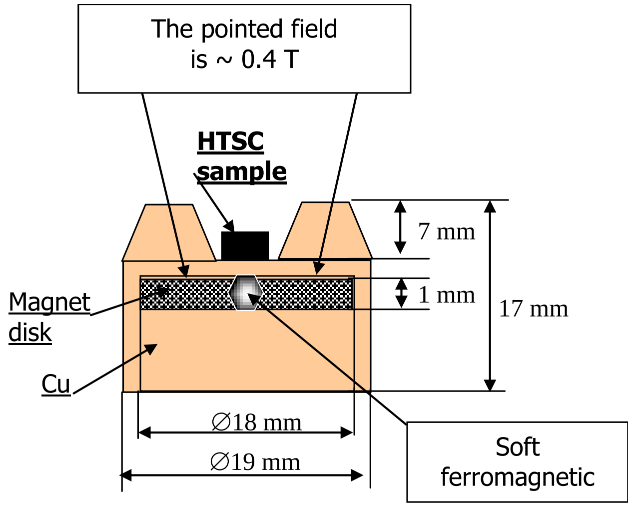
Sample size: 8 x 2 x 2 mm; Magnet: SmCo, B = 0.4 T



HTSC samples made at LPI

- material: superconducting ceramics $YBa_2Cu_3O_{7-x}$

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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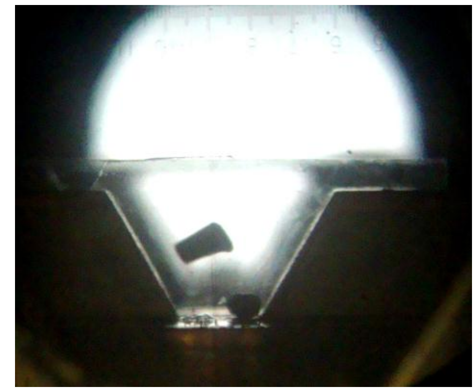
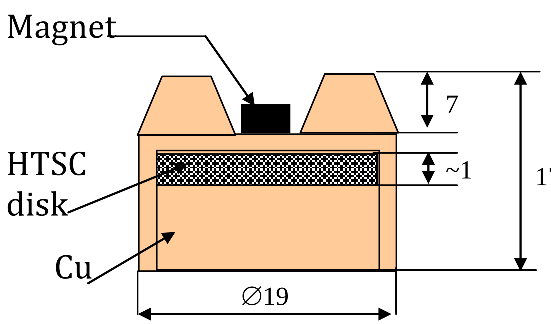
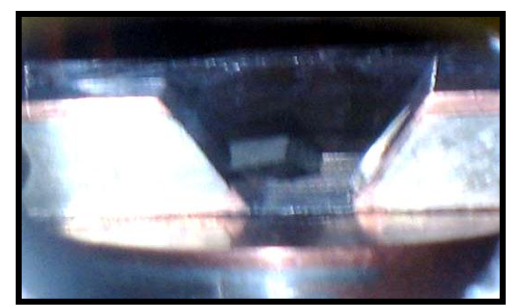


HTSC- sample levitation over a magnet, T=18 K



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

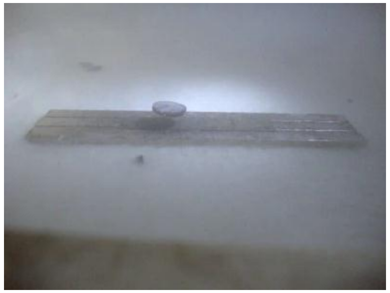
PMG:
4 permanent magnets
Magnet:
SrBa ferrite, 0.18 T
Screw insert:
soft ferromagnetic ARMCO
CH shell:
2-mm-diam

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

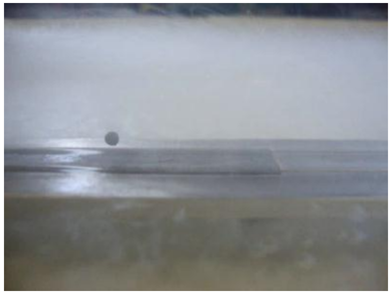
Magnet (commercial):
Ferrite F8
B~0.16 T
OD 15 mm
ID 9 mm
5-mm-thick
Sample (made at LPI):
YBaCuO ceramics
Size ~ 2mm

❑ 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)



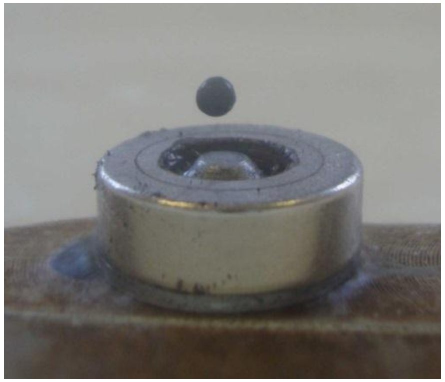
HTSC pellet ∅ 12.4 mm



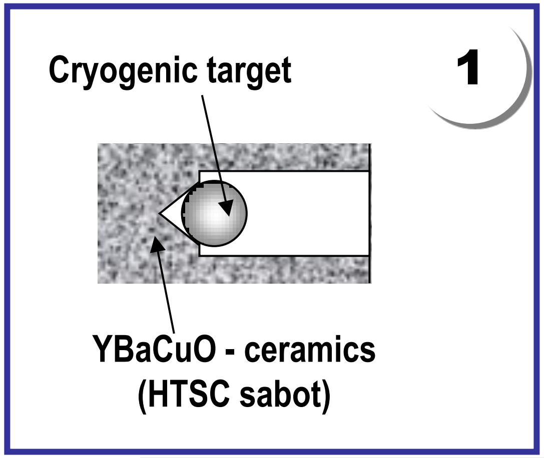
HTSC coated CH shell ∅ 2mm

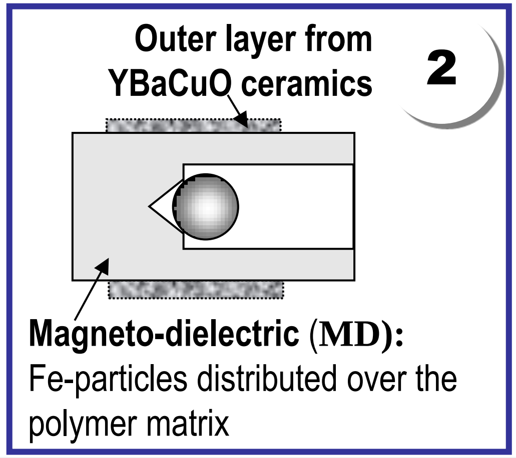
❑ Stable levitation of the CH shell with the outer YBaCuO layer

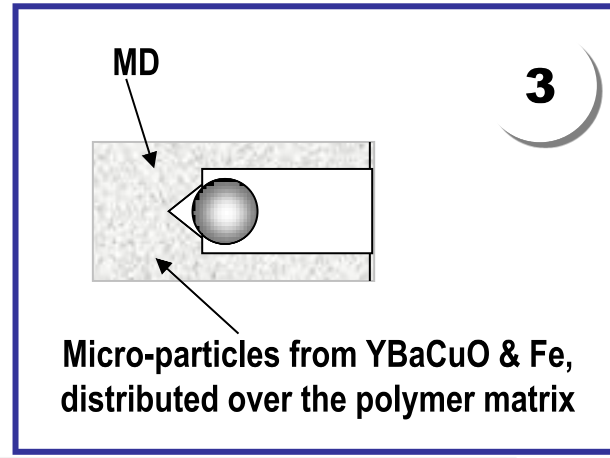
Magnet: ferrite F8,
B~0.2 T,
OD 14-mm,
4-mm-thick
CH shell:
2-mm-diam
YBaCuO layer:
~10-um-thick



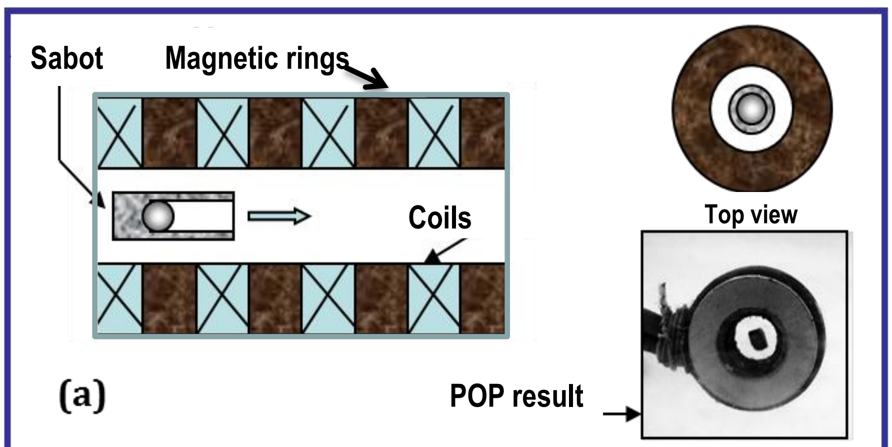
Different designs of a maglev sabot based on using superconducting ceramics YBaCuO

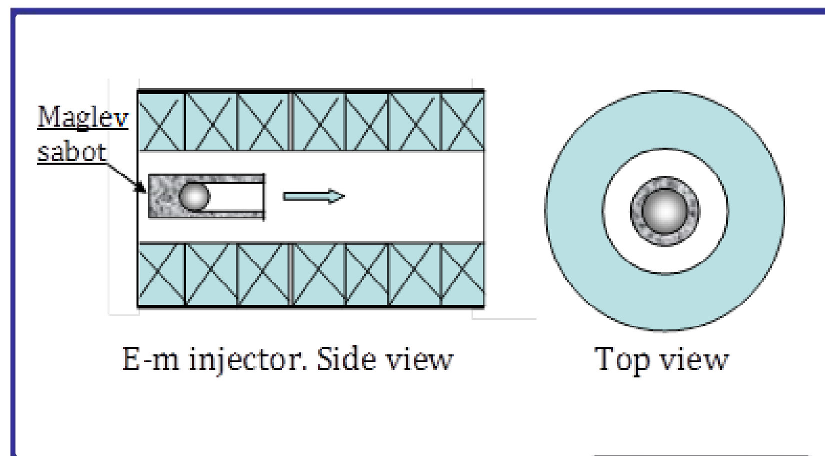






Sabots for almost frictionless motion inside the electromagnetic injector, which enhance the operating efficiency of the maglev accelerator





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

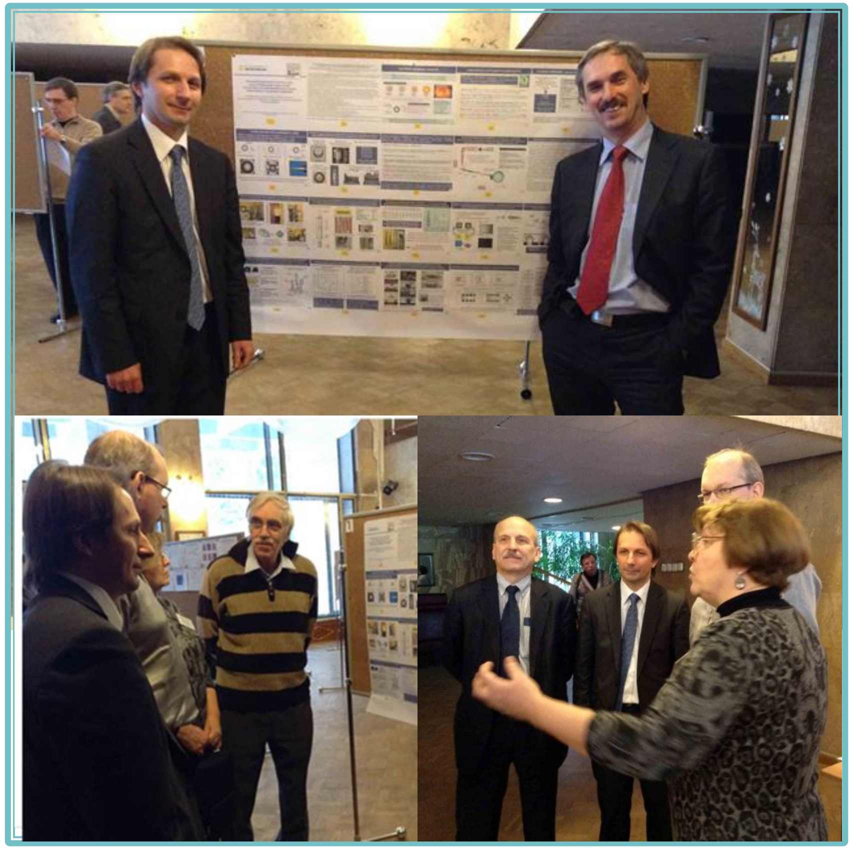
We are going to realize the CTF concept based on FST in the next generation project

- **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 25th 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:

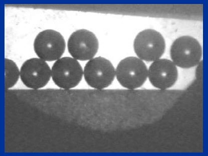
  ⇒ Fueling a batch of free-standing targets (up to 1000 atm D_2 at 300 K),
  ⇒ Fuel layering inside moving free-standing targets using FST technology: cryogenic layer up to 100 um-thick,
  ⇒ Target injection into the test chamber with a rate of 0.1 Hz
  ⇒ Target tracking using the Fourier holography approach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

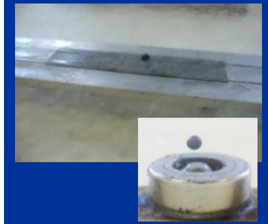
- **LPI continue developing the of R&D program on CTF** in collaboration with Power Efficiency Center of INTERRAO UES & National Research Center "Kurchatov Institute". **New generation project is under consideration.**

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