University of Latvia Institute of Physics

Institute of Physics
of
University of Latvia (IPUL)

Activities in liquid metal and MHD-technologies

2000-2005

Latvia, Salaspils

University of Latvia Institute of Physics

CONTENT

Institute of Physics
of University of Latvia
32 Miera Street, Salaspils
LV-2169, Latvia

www.iph.sal.lv
fizinst@sal.lv
fax +371 7901214

INTRODUCTION

The Institute of Physics of the University of Latvia is one of the main research centers in the field of MHD technology which has been involved in both theoretical and applied studies and experimental work.

The research activities of the Institute are concerned with:

- the investigation of MHD phenomena in incompressible conducting media: channel flows, jet and drop flows, flows around bodies, MHD turbulence, flows caused by the interaction of the current present in the liquid medium with its own magnetic field;

- the study of flows in high-power conduction MHD channels in both the pumps and throttles relevant to fast neutron reactors;

- the developing new types of MHD-machines, which could be used for pumping liquid metal heat carrier in the primary radioactive loop of fast reactor;

- the study of effects relevant to magnetization of liquid systems as well with heat mass transfer process in paramagnetic solutions, electrolytes, magnetic colloids and biological systems;

- the activity in the field of designing, manufacturing, and implementing into various industries the main types of MHD devices; EMPs, flowmeters, throttles, devices for aluminum and its alloys.

The Institute of Physics possesses a special Mercury laboratory complex including a 350m^2 experimental hall. The amount of Hg in use reaches 13.10^{3} kg, almost 1m^3 mercury. The same can be said about new technologies for Hg chemical treatment /purification/ Mercury is used as an effective modeling material for investigation of a great number metallurgical processes, as well as for thermohydraulic testing of systems, proposed for other / more aggressive or high temperature/ heavy liquid metals.

Some examples of Institute activities in the MHD technology during the last years are presented in this Report.

1. PARTICIPATION IN NEUTRON SPALLATION PROJECTS

1.1. LIQUID METAL TARGETS FOR PARTICLE BEAM TRANSFORMATION

MEGAPIE

If high enough energy (at least a few hundred MeV) protons are targeted into a dense material they excite the so-called spallation reaction and produce neutrons. This reaction is rather effective. So, in lead more then 10 spallation neutrons can be generated by one proton. Potential applications for liquid metal proton/neutron converters are connected with the ideas to start generating neutrons for general research in a more effective way, with new energetic characteristics, in short/sharp or long pulses, etc. May be, even cheaper. An essentially different version is also under consideration - to use the spallation neutrons for sustaining the chain reaction in so called Accelerator Driven Systems (ADS), in other words, fission reactors with initially sub-critical cores.

In last years IPUL has established definite relations to both these directions, a few examples will be presented below. So, IPUL is participating in the project MEGAPIE (Megawat Pilot Target Experiment), aimed at the demonstration of the feasibility of a lead-bismuth targets for spallation facilities at a beam power of level of one MW.

Design and production of the two arranged in tandem induction pumps for the Megawatt Pilot Target Experiment MEGAPIE should be considered as one of the most complex technical tasks ever solved at IPUL. The pumps will be operated submerged in PbBi eutectics. Depending on the proton beams trip the temperatures can change in range 230-380 ^{0}C with a rate of up to 10^{0}C/s. The main pump maintains the flow (4 L/s; 200mbar) between the beam entrance window and the heat exchanger. The by-pass pump (0.35 L/s; 350 mbar) controls the flow structure in the direct vicinity of the window. A special test rig was installed at IPUL containing 100 L of PbBi, at controllable (200-450^{0}C) temperatures, ensuring flow rate 5L/s for the main pump and 0.5L/s for the bay-pass pump. The system of pumps + flowmeters was successfully tested over 600 hours.

The pictures of the induction pump system designed under such complicated conditions are presented in Fig. 1-4

Preliminary technical design of the MEGAPIE spallation target

Sketch of a preliminary design of the MEGAPIE spallation target

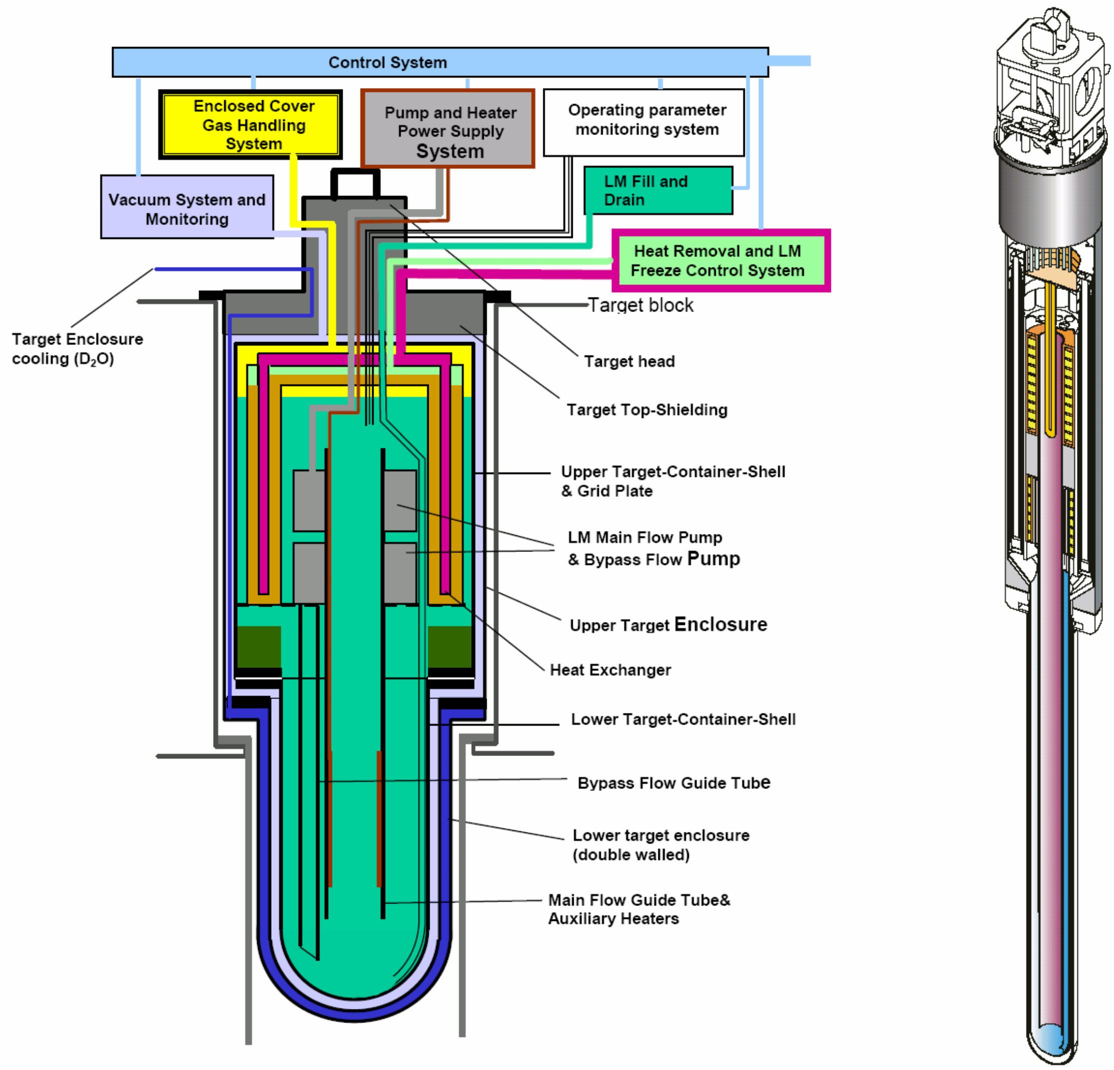


Fig. 1

<u>Subject of the MEGAPIE-TEST Project are</u> -
to develop, improve and validate expertise, knowledge and experience about the design and the operation of a HLM spallation target and to verify its feasibility under realistic operating conditions

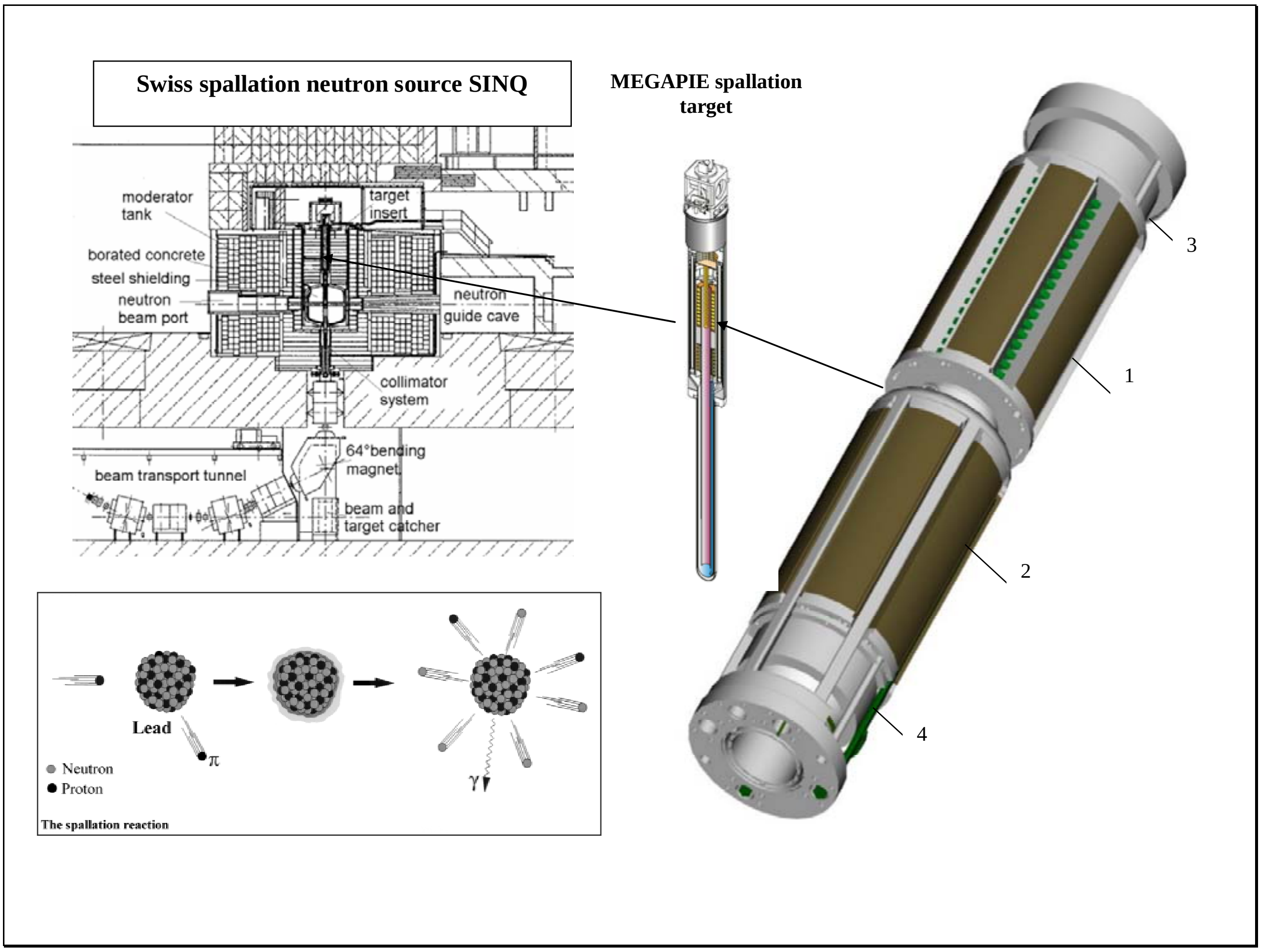


Fig.2

Electromagnetic Pumps System (EMPS)

Why IPUL take part in the MEGAPIE Project?

Previous experience in the frameworks of preparation for pilot flight to Mars.

EMPs - Maintains LBE flow between MEGAPIE target's Heat Exchanger and proton beam entrance window to ensure thermal power evacuation

EMPs - Heart of the spallation target

Operating conditions:

Duration of operation, hours	up to 10 000
Medium, eutectic	Pb Bi
Temperature, C	240 – 380
Rate of temperature change, C/s	up to 5-10

Physics

Fig.3

ELECTROMAGNETIC PUMP SYSTEM

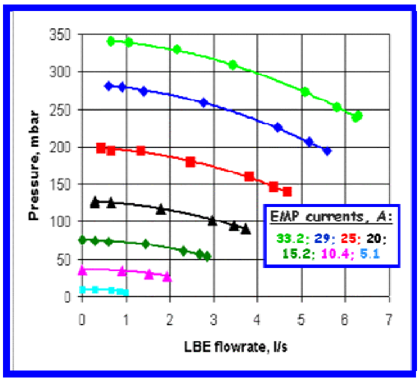
Peculiarities of operating

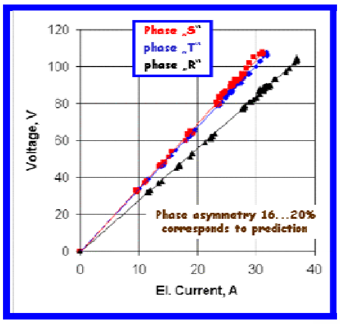
- **Restricted space of pumps;**
- **Fluctuating of temperature;**
- **Mechanical stresses'**
- **Irradiation**

Requested parameters:

Parameter	Unit	ENP 1	EMP 2
Nominal LBE flow rate	L/s	5	0.35
Pump's pressure	Bar	0.2	0.5
Power	kVA/kW	9.8/8.2	8.1/6.8
Current, 50 Hz, 3-ph	A	30	30
Voltage ph/lin	V	108/182	90/156
LBE temperature	^{0}C	280-300	240-280
Bound dimensions	mm	∅ 226 x	380

EMP1 Operating Characteristics





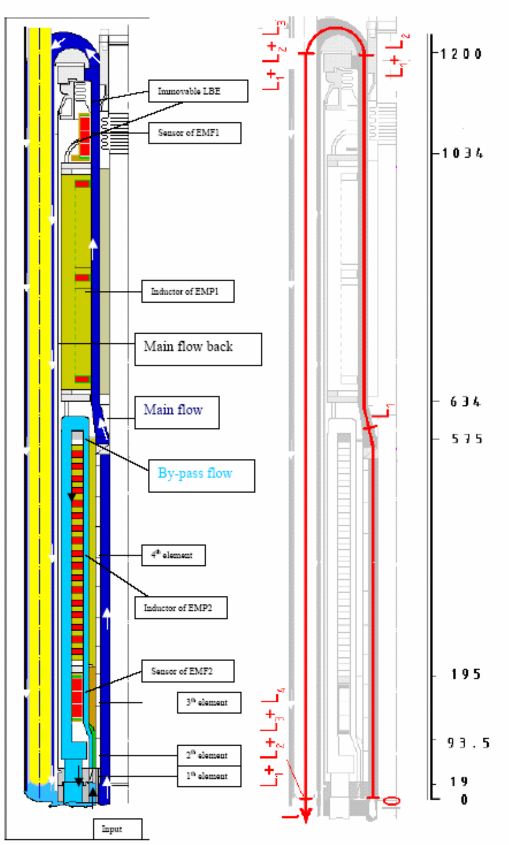
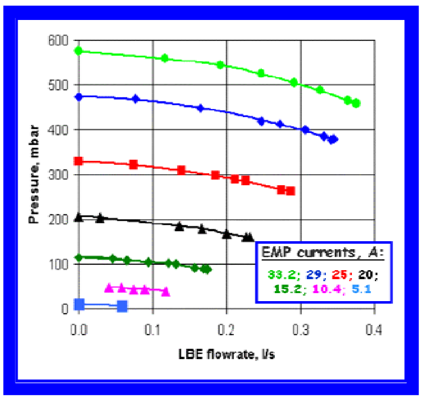


Figure 1. Schematic of PbBi flows in EMPS. Figure 2. Main flow loop.

EMP2 Operating Characteristics



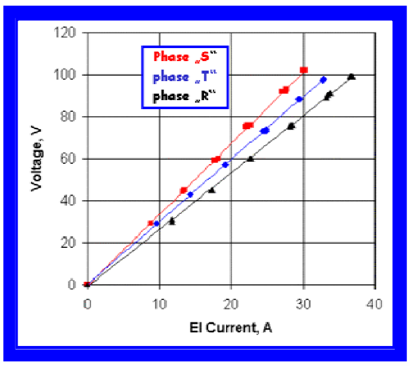


Fig. 4

Beam entrance window

So, the MEGAPIE project at IPUL was started not with the design of MHD equipment, but with a careful investigation of flow conditions in the vicinity of the beam entrance window. A scale 1:1 hydraulic replica of the proposed target was installed in the large Hg loop of IPUL, (Fig.2).

The general scheme of the flow inside the target is clear- in the intensively heated central part upwards, then through a heat exchanger, the pump and back along the outer walls of the cylinder. But it is clear also, then in such a case directly in the central point of the cup a “dead liquid zone” can appear and directly here the beam reaches its maximum intensity. To overcome this difficulty in the accepted version it was proposed to organize an additional bypassing jet, washing directly the beam entrance surface. Practically it means, to introduce in the targets body a second independent hydraulic track.
The power density on the beam entrance window will reach 30 kW/cm ^{2}, the heat deposition in the solid wall as well in the close-lying liquid metal will exceed the level of 1 kW/cm^{3}.

Optimization flow conditions in the vicinity of beam entrance window

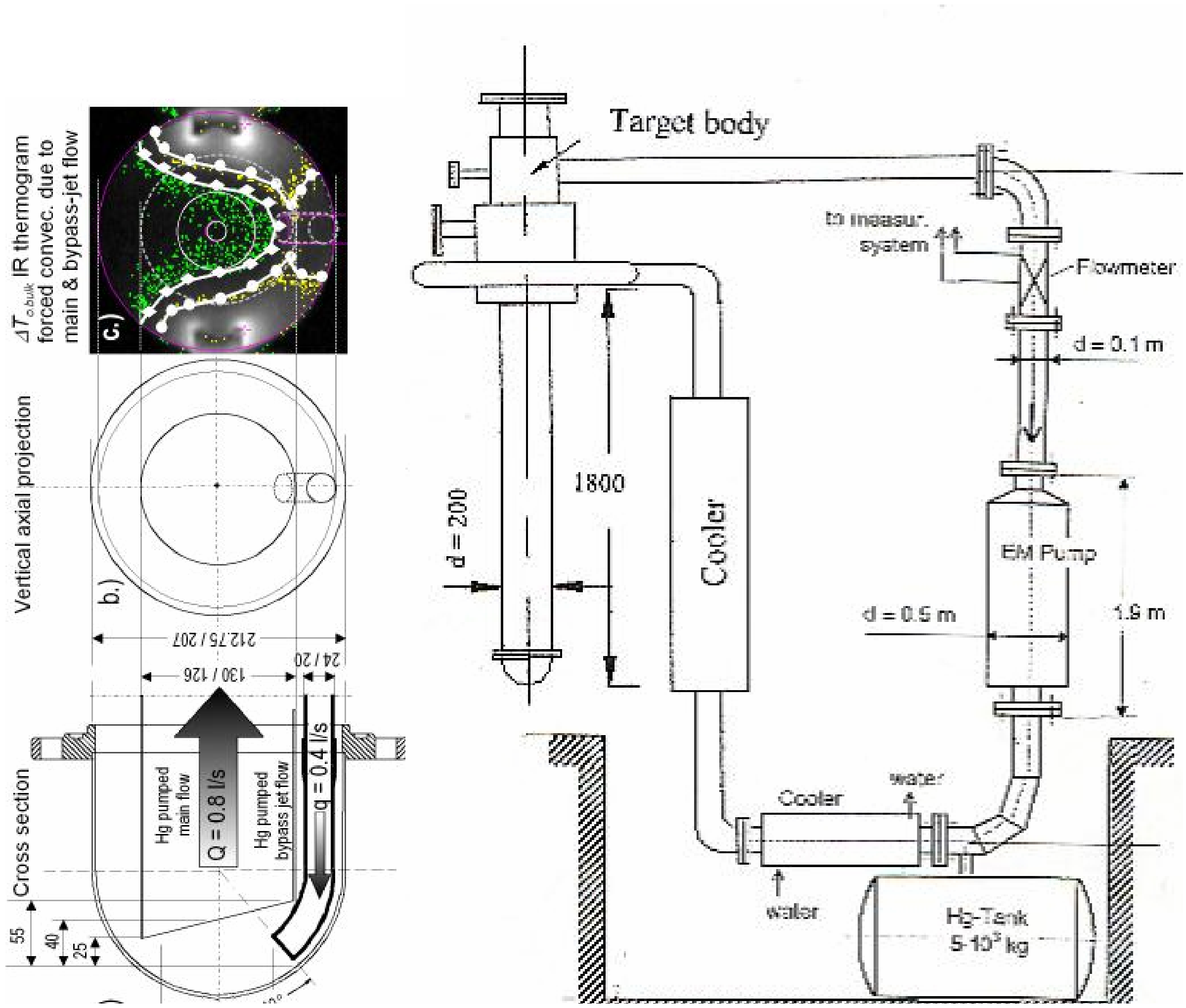
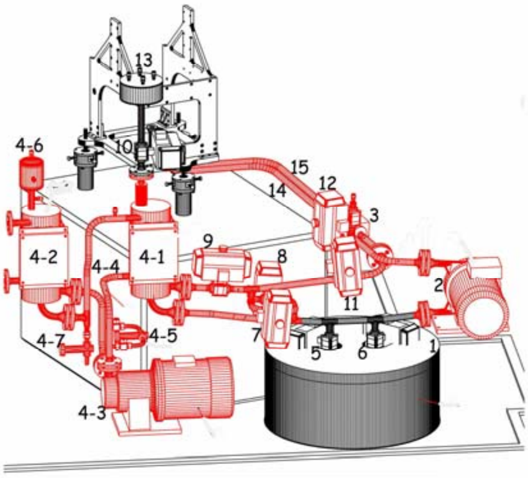


Fig.5

LiSoR Pb – loop

To make an estimate for the life-time of the beam entrance window it should be remembered that the heat is generated by an intense particle beam which can essentially influence also the structure of the wall material. IPUL is participating also in the LISOR (**Li**quid metal **So**lid metal **R**eaction) experiment, an R&D sub-project of the MEGAPIE at PSI. Our task was to deliver the central component of the stand, the main liquid metal (PbBi) loop, a rather complex (see Fig.6) facility /-/. It was designed to provide in the test section a stabilized flow rate 0.2 l/s (linear velocity 0.9 m/s) under specific conditions typical to in-beam tests: restricted area, ambient temperature up to 60^0C, radiation field, etc.

Lead bismuth eutectic loop for LiSoR facility
LBE loop for LiSoR experiment at PSI



1-LBE tank (25 l), 2-induction pump; 3-electromagnetic flow meter; 4-thermostat (4-1 and 4-2-LBE-DIPHYL and DIPHYL-WATER heat exchangers; 4-3-oil pump; 4-4-Ventury tube; 4-5-bypass; 4-6-oil expansion tank; 4-7-valves for oil loop filling and draining) 5…12-automatic valves; 13-expansion tank; 14 and 15-inlet and outlet pipe.

Fig. 6.

WINDOWLESS SPALLATION TARGET

It is the right place directly here to remember on the ideas about windowless liquid metal targets. It was mentioned that in SINQ by special magnets the proton beam is bent upwards. In principle, the beam could be bent also downwards and targeted against an open free liquid metal surface. On a definite phase IPUL was collaborating with the Belgian Nuclear Research Centre on design and verification experiments for the Windowless Spallation Target of the ADS Prototype MYRHA, planed as a small high-performance irradiation facility with fast neutron fluxes up to 10^{15} n/cm^2/s.

The target absorbs from the beam 1.75 MW, about 80% of this power remains deposited in the liquid metal as heat. To carry it away flow rates of the order 10 l/s are required. The desirable free surface flow structures need to be established taking into account the strong geometrical constrains, the thermal and vacuum requirements. Again, a special chamber (Fig.7) was installed in the already mentioned large Hg facility, allowing to test in scale 1:1 different verifications of the hydraulic scheme, selected after numerical modeling and water pre-testing.

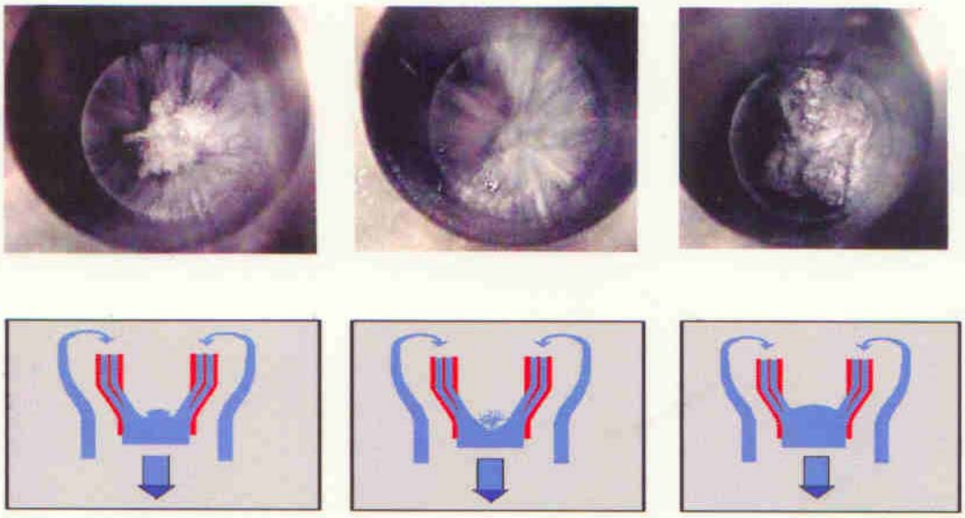
In a cylindrical nozzle the upward flow must be turned back and evacuated through a central channel. For this transfer process such parameters should be chosen that in the central part of the nozzle a clearing ore zone appears where the free surface remains enough flat and stable for particle beam reception. Observations and video-records through the chambers window confirmed that such parameters can be achieved.

Hg Modeling of MYRRHA at IPUL

The work has been conducted in Riga to demonstrate the feasibility of the windowless target designed by the MYRRHA team.

Vertical mercury loop
Volume 100 L; Q - 11 L/s

Full scale model
of windowless target



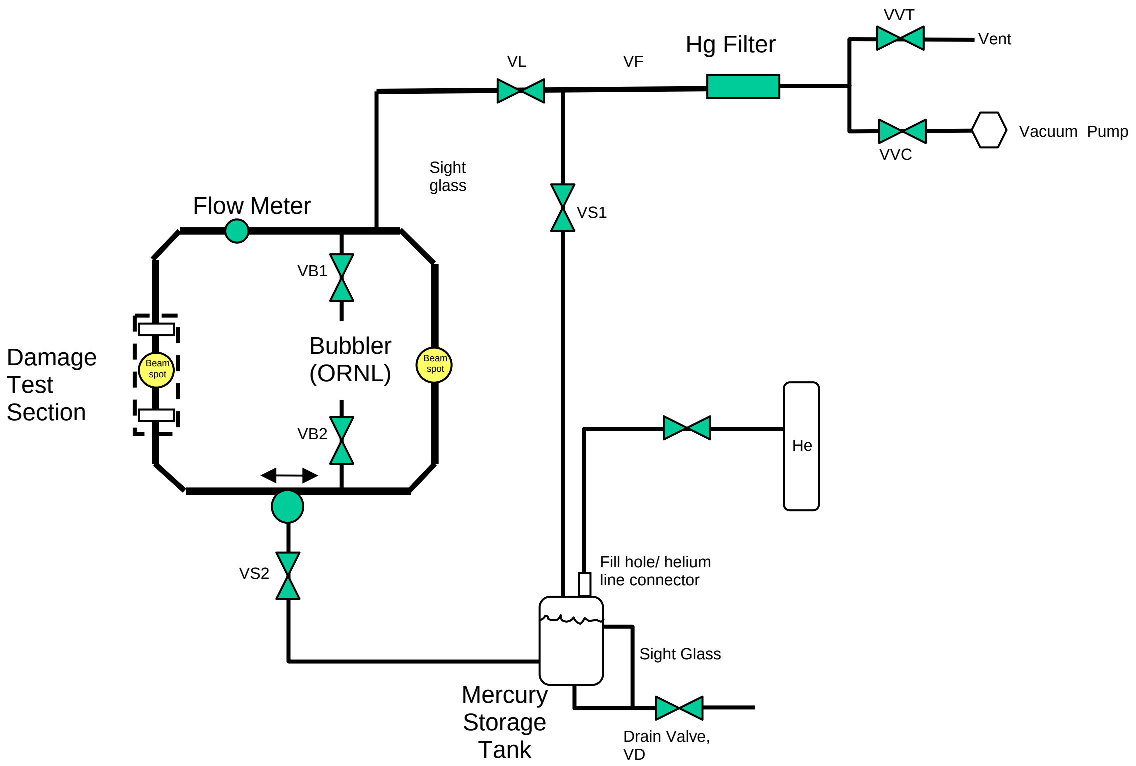
Free surface structures at different filling levels

Full paper presented at AccAPP-ADTTA'01 conference, Reno,NV,USA,11-15 November 2001
K.Van Tichelen, P.Kupschus, B.Arien, H.A.Abderrahim, A.Kljukin, E.Platacis, **"Design and Verification experiment for the Windowles Spallation Target of ADS Prototype MYRRHA"**

Fig.7

1.2 MERCURY LOOP FOR IN-BEAM TESTS

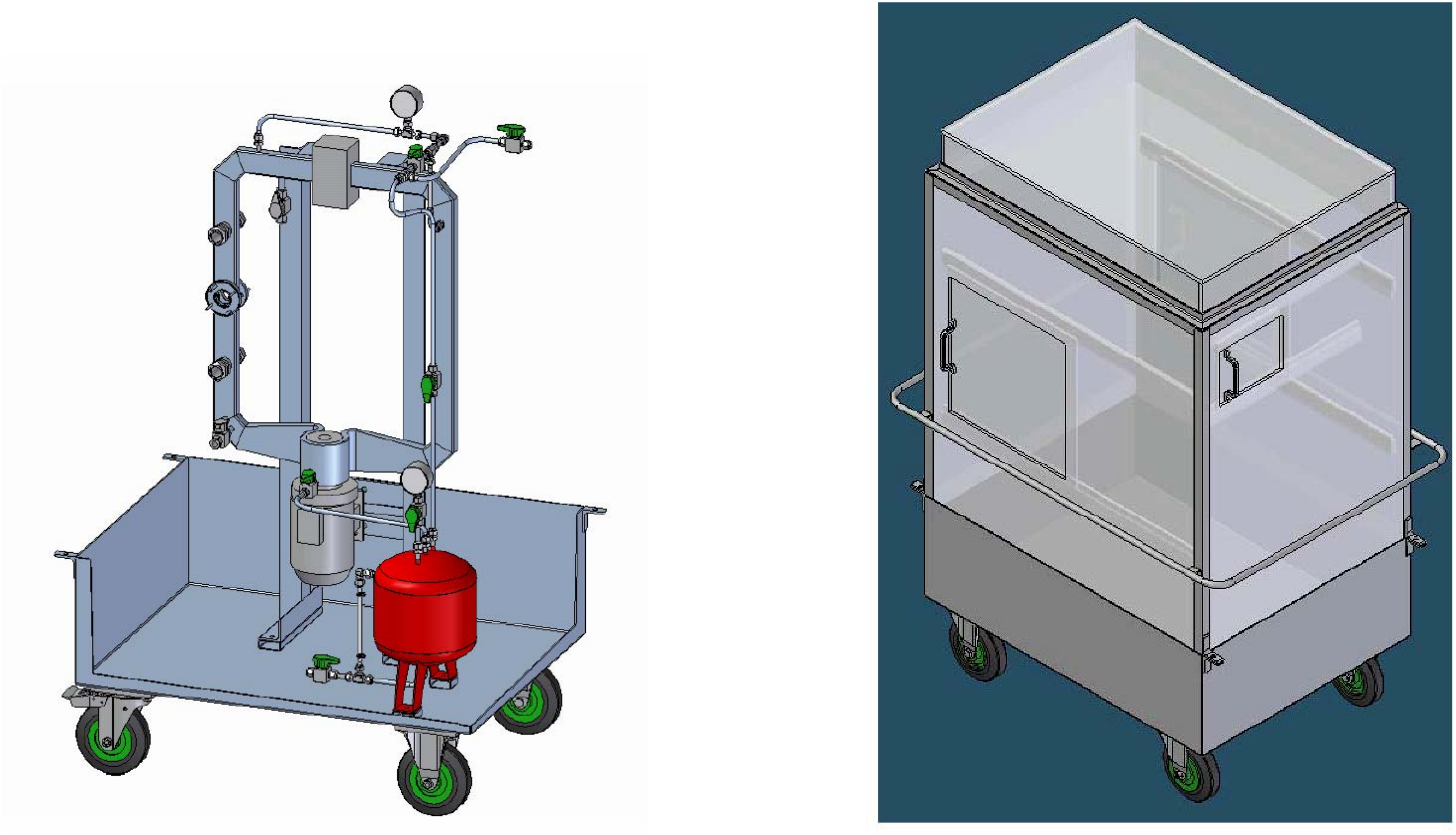
Designed and fabricated under contract
between Institute of Physics of the University of Latvia and
Oak Ridge National Laboratory



In-beam mercury test loop schematic.

The main loop piping:

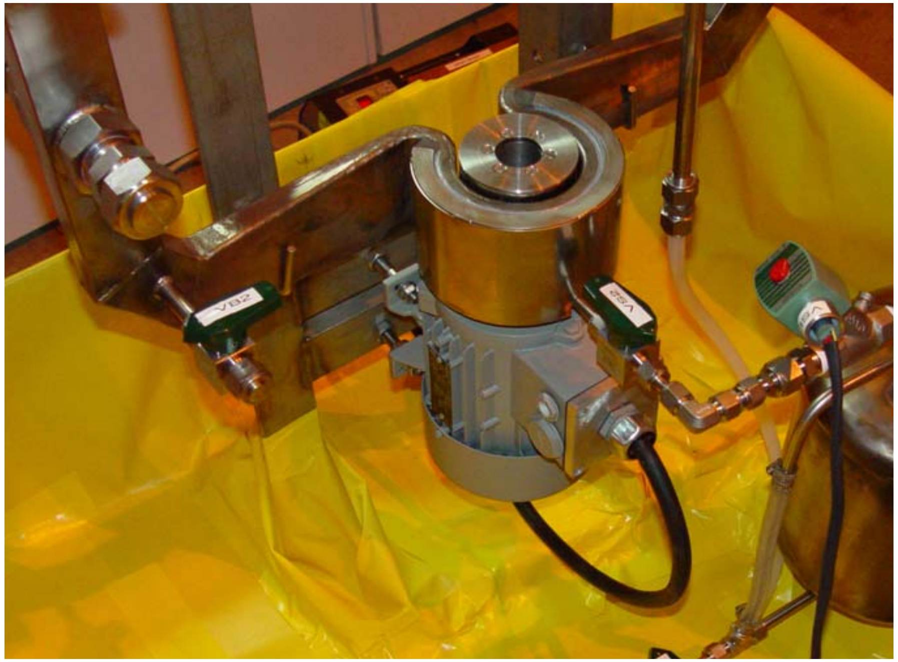
• Rectangular cross-section, mm	25 x 50
• Thickness of the walls, mm	1.5
• Inner cross-section, cm^2	10.34
• Mercury flowrate through the loop. L/s	0.45
• Operating pressure at mercury free surface atmospherical maximal pressure in the storage tank, bars	2.5
• Loop inventory,	about 3
• Mercury storage tank volume, L	7
• Maximal operating temperature, ^0C	90

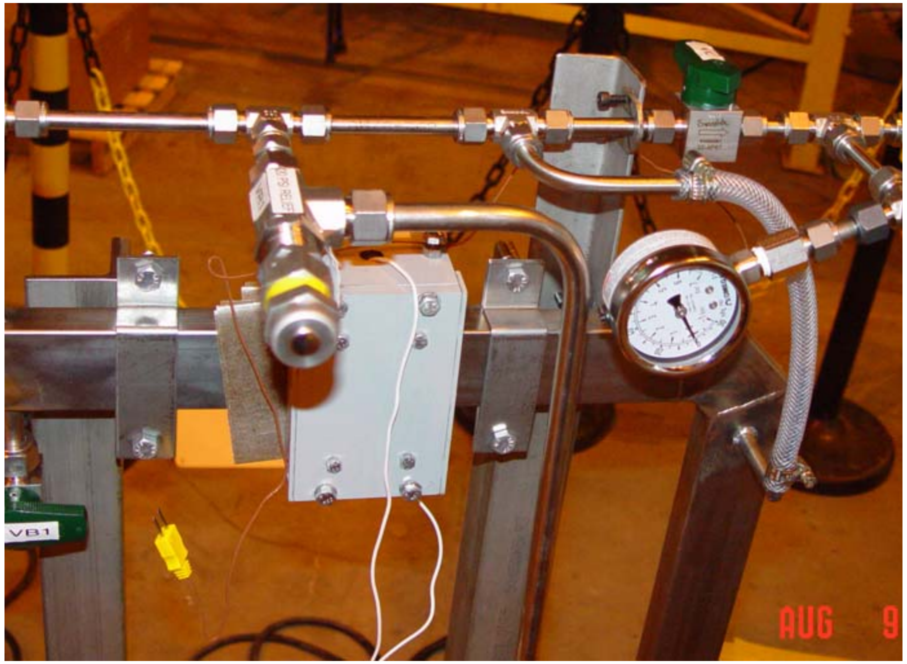


In-Beam Test Hg Loop and secondary container.

Ready fully assembled loop in secondary container at IPUL just before shipping to ORNL

Loop delivered and installed at ORNL



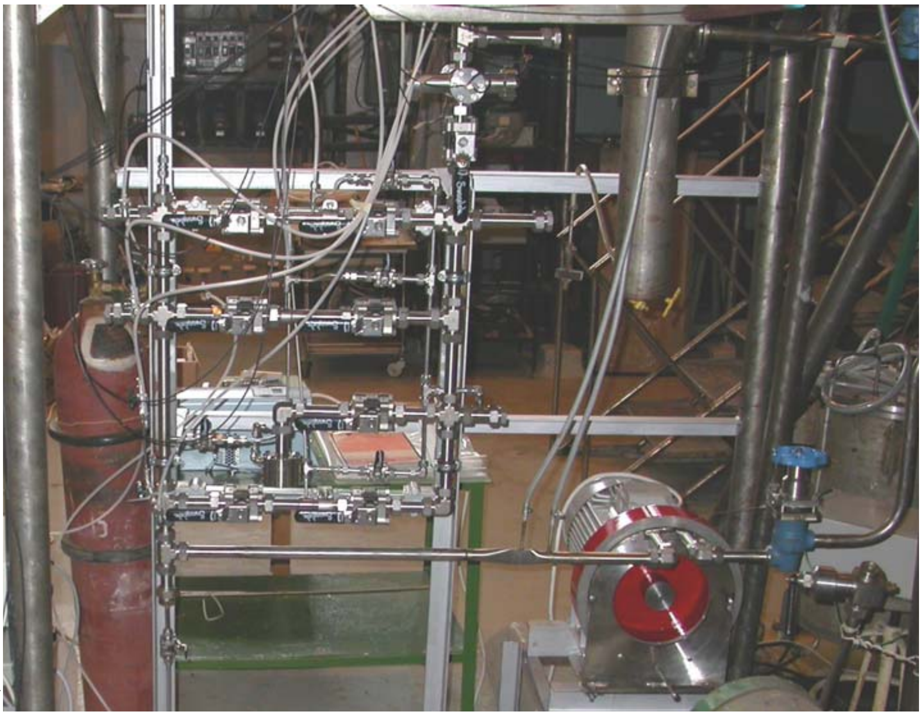


Electromagnetic Induction pump on permanent magnets installed in In-Beam Test Hg Loop (provided flow rate 0.5L/s)

Electromagnetic conduction flow meter (sensitivity of flow meter – 5.8 mV per 1.0L/s)

1.3 INVESTIGATION OF THE LIFE TIME OF GAS BUBBLES IN MERCURY FLOW

MERCURY STAND



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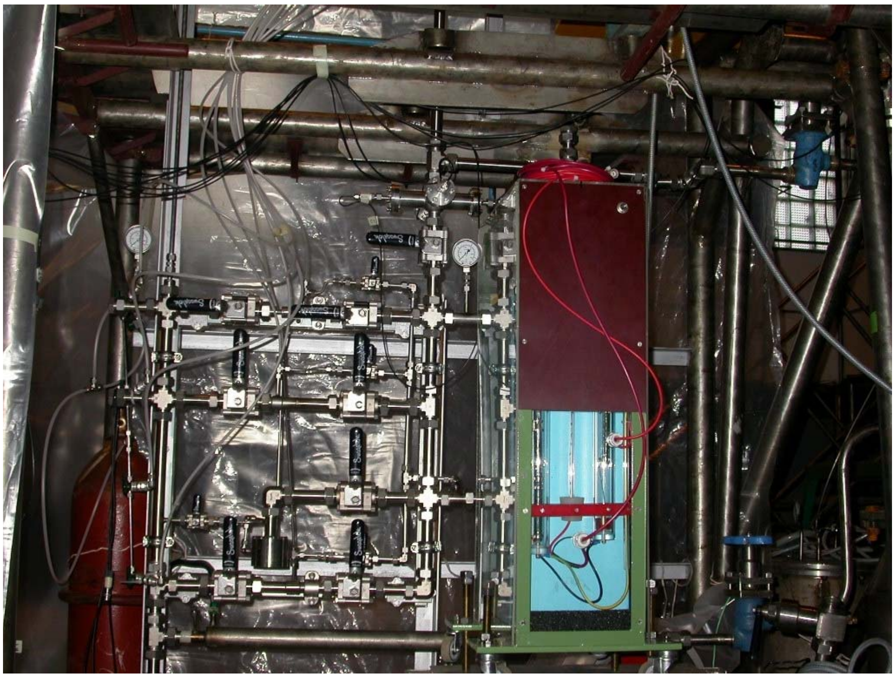
By-pass mercury loop for injection gas bubbles into big Hg-loop for investigation of life time of gas bubbles in mercury flow.

In mercury by-pass loop the specially for this purpose designed and produced at IPUL Electromagnetic Induction Pump on Permanent Magnets have been installed for developing rather high pressure (up to 8 bar) at maximal operating temperature 100^{0}C.



Test Section for generating of different sizes gas bubbles in the mercury.

2. TARGETS AND ION SOURCES FOR EURISOL

EURISOL project is under developing.

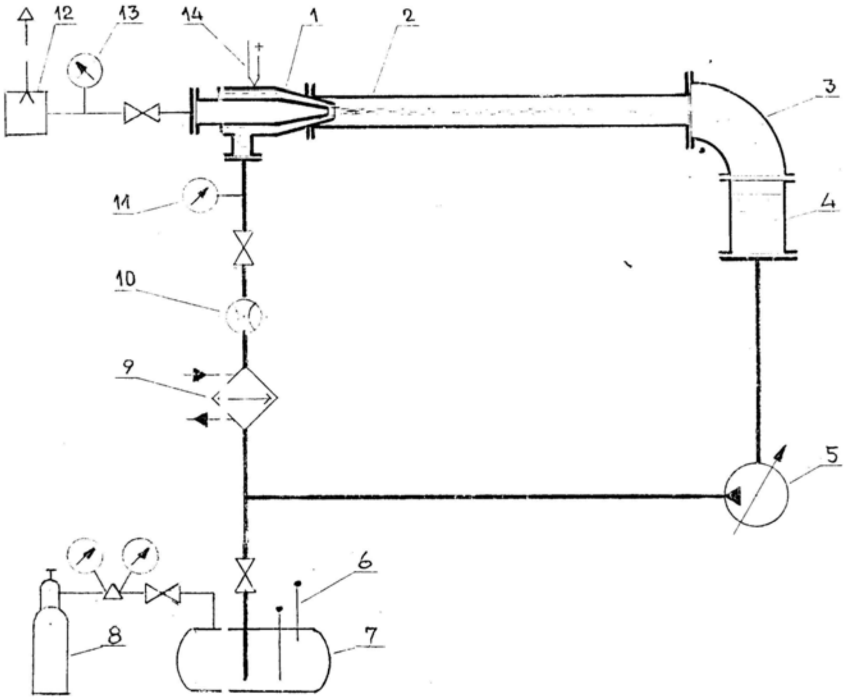
IPUL task is **engineering design and construction of a functional Hg-loop for a continuous Hg-jet at ~ 30 m/s and diameter 10-20 mm.**

For a power density about 10^3 MW/m^3 the windowless, free surface, molten Hg-jet is proposed as target.

The typical parameters of the converter target would be:

- Power absorbed in Hg-jet, MW — 1
- Operating pressure, bars — 100 ?
- Flowrate, t/min — 2 (~2.5 L/s)
- Jet speed, m/s — 30
- Temperature:
  - Inlet to target, ^{0}C — 30
  - Exit from target, ^{0}C — 100
- Total Hg inventory, t — 10
- Pump power, kW — > 50

Initial scheme of Hg-loop



Technical parameters

Liquid medium	Hg
Speed of the jet i, m/s	30
Diameter of the jet, mm	10
Productivity, L/s	2,45
DN of the loop tube, mm	50
Flow speed in tube DN50, m/s	1

Fig.

1-nozzle; 2-jet chamber; 3-reflector; 4-tank; 5-pump; 6-level indicator; 7-Hg tank; 8-bottle with inert gas; 9-heat exchanger; 10-flow meter; 11-manometer; 12-vacuum pump; 13-vacuummeter; 14-thermocouple.

3. LIQUID METAL MHD IN FUSION RELATED TASKS.

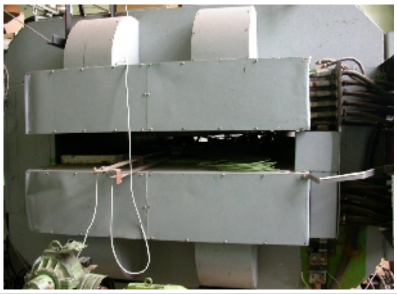
3.1. LIQUID METAL MHD RESEARCH IN MAGNETIC FIELD

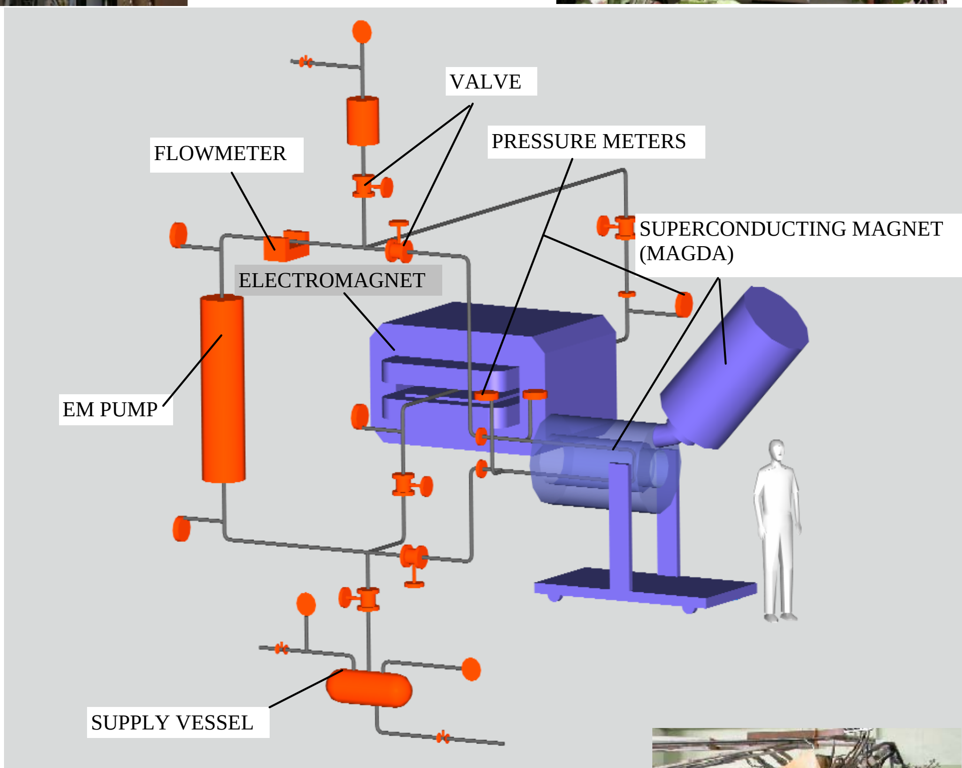
Also IPUL has made an essential profit on the easy enough demonstrable relation of MHD to fusion. Mainly, to develop a strong, in a definite sense even unique experimental base for liquid metal MHD research, this remains technically inviting also today. As an illustration a really installed room temperature InGaSn loop, equipped with a 80 tones electromagnet and a 5 Tesla superconducting magnet, is presented. In the main cases of the real live, to use both these magnetic systems they ware equipped with individual essentially smaller liquid metal loops. The bulk of the required information was connected with MHD problems inside the self-cooled (leading at that time) Li or PbLi blankets – pressure losses, velocity fields, ideas to maintain a definite level of turbulence in a quasi-2D form, etc. A few “non-ordinary” information records should also be remembered. Following experiments were performed in the superconducting magnet. Using a 80% Bi and 20%Sn binary system as a modeling liquid it was shown that a strong magnetic field is able to prevent the segregation of both the components. Such a result correlates with one of the problems today, namely, how to become sure that under the complicated working conditions the blanket composition PbLi can not start separate, for example, because of deviating away from ideal eutectics. It was demonstrated also, that a strong magnetic field stabilizes systems of close laying liquid metal jets issuing from an array of nozzles, a result directly related to the recently taken up again ideas about liquid metals as power and particle receptors inside the vacuum chamber.

Stand for liquid metal MHD research

EM Pump
pressure 5 bar
flowrate 5 l/s
medium InGaSn

Electromagnet
gap size,m 3x0.5x0.155 3
field strength, T 1.8
weight, tones 83





Superconducting magnet

diameter of the working space, mm	320
length of solenoid, mm	780
max field strength in the center of solenoid, T	5.06
length of 5% field uniformity, mm	580

3.2 INVESTIGATION OF CORROSSION EFFECTS OF EUROFER STEEL IN Pb-17Li STATIONARY FLOW

OBJECTIVES:

- **Evaluate of magnetic field effects on EUROFER corrosion in magnetic field at 550 ^{0}C**
- **Three 2000 h long campaigns to carry out**

Pb-17Li facility is constructed – for long run experiments for ASSESSMENT OF MAGNETIC FIELD EFFECTS on EUROFER CORROSION in Pb-17Li

Main parameters of the Test facility:

Operating temperature in the Test Section (hot part), ^{0}C	550
Intensity of magnetic field, T	1.7
Operating temperature in the loop (cold part), ^{0}C	350
Velocity of the Pb-17Li in the Test section, mm/s	50

Principle scheme of Pb-17Li loop

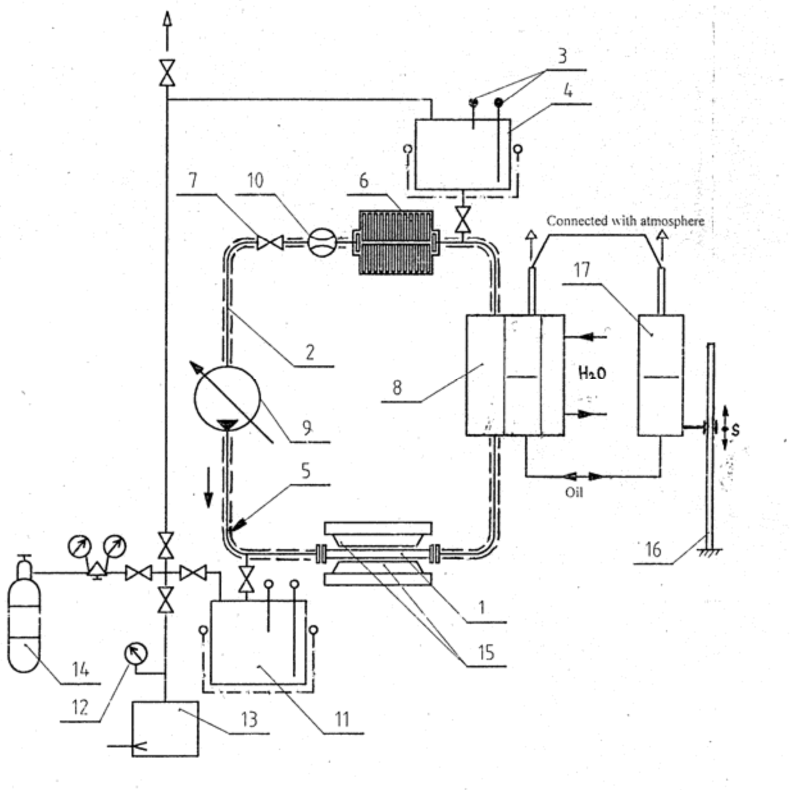


Fig.

1-test section; 2-LM loop; 3-level meters; 4-expansion tank; 5-heaters; 6-cold trap; 7-flow adjusting valve; 8-heat exchanger(LM-oil-water); 9-EM induction pump; 10-flowmeter; 11-supply tank; 12-manometer; 13-vacuum pump; 14-gas balloon; 15-poles shoes; 16-lifting device.

Liquid metal Pb-17Li loop
for EUROFER steel corrosion
experiments in magnetic field
at temperature of melt $T = 550^0C$

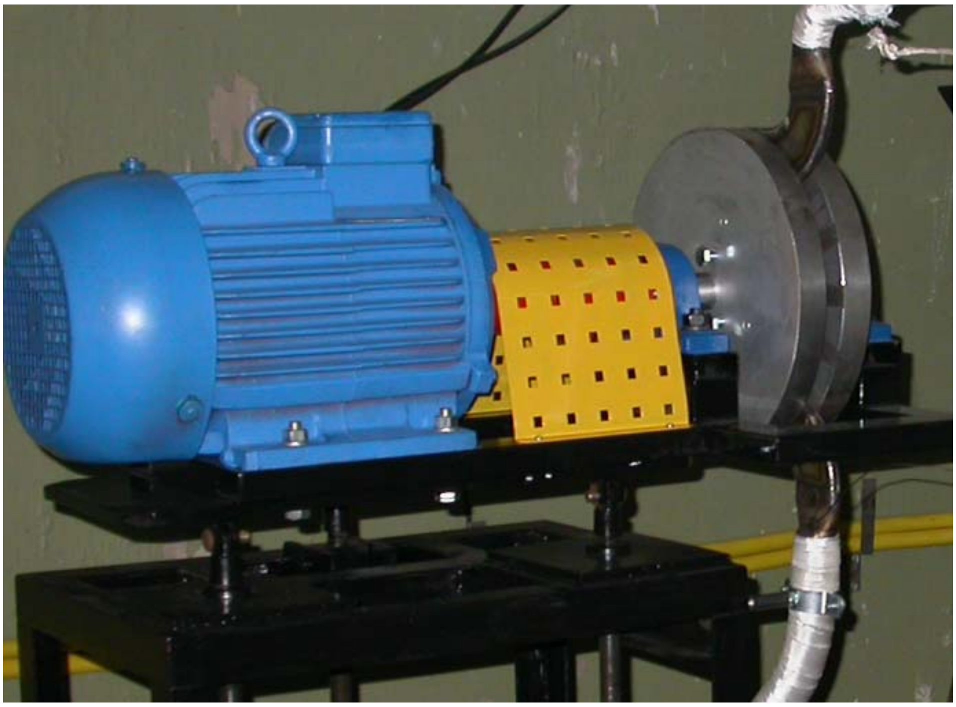
Stand of Liquid metal Pb-17Li loop

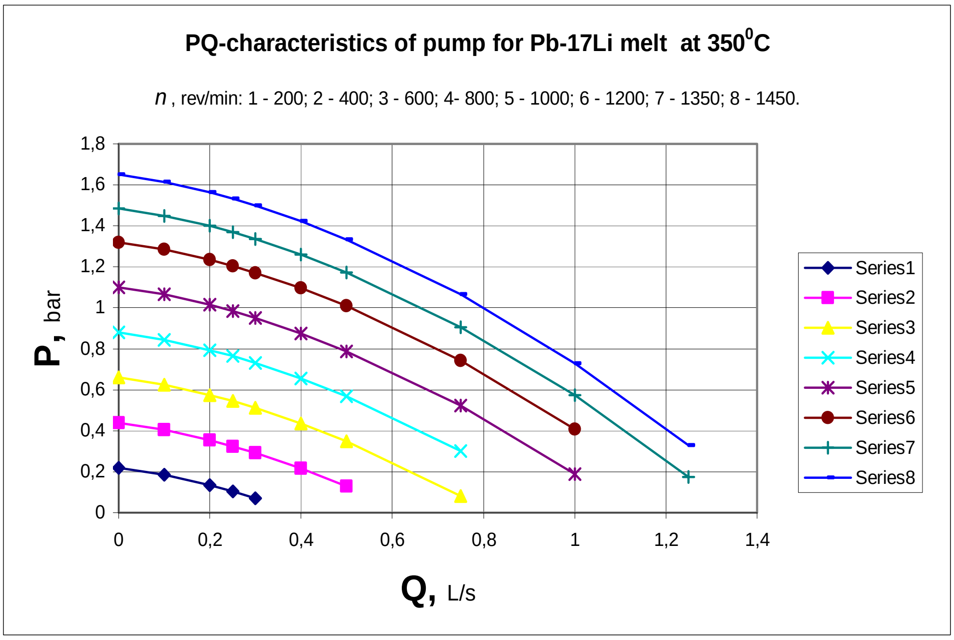
for carrying out long run experiments for assessment of magnetic field influence on the corrosion processes of EUROFER steel (*candidate material for the construction of the blanket of fusion reactor ITER* **) in Pb-17Li stationary flow at high temperatures**

Main parameters :

magnetic field strength up to 2 Tesla;
averaged flow velocity in the Test Section up to 5 cm/s;
operating temperature in the Test Section up to $T = 550^0C$;

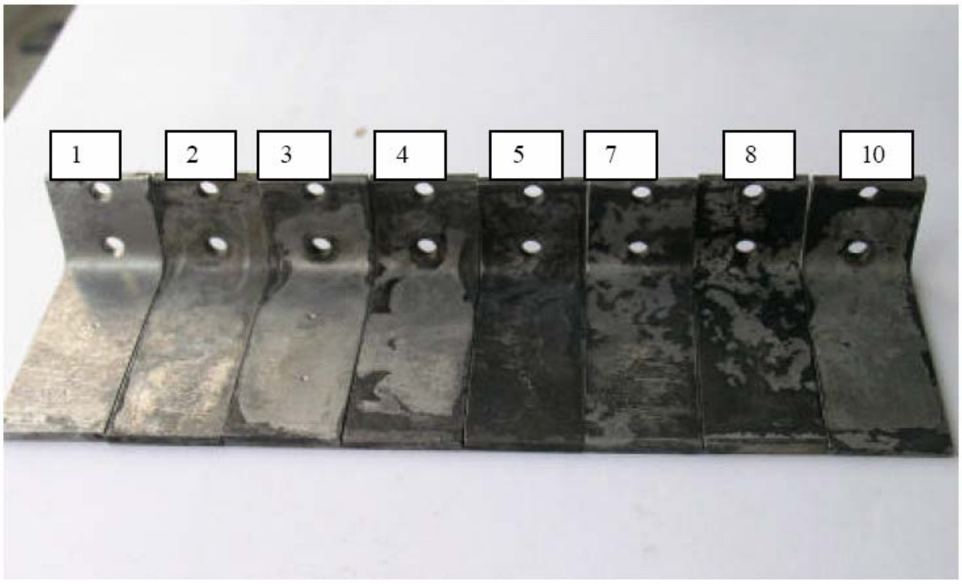
Up till now two experimental sessions (each 2000 hours long) have been finished successfully, now the third session (also 2000 hours long run) will be continued.



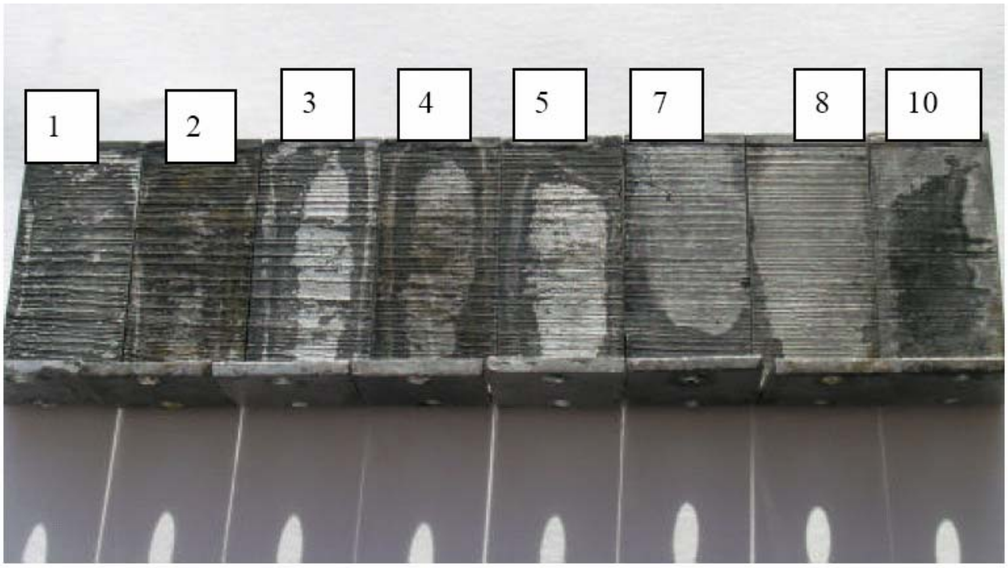


Electromagnetic Induction Pump on permanent magnets installed in Pb-17Li loop for corrosion experiments.

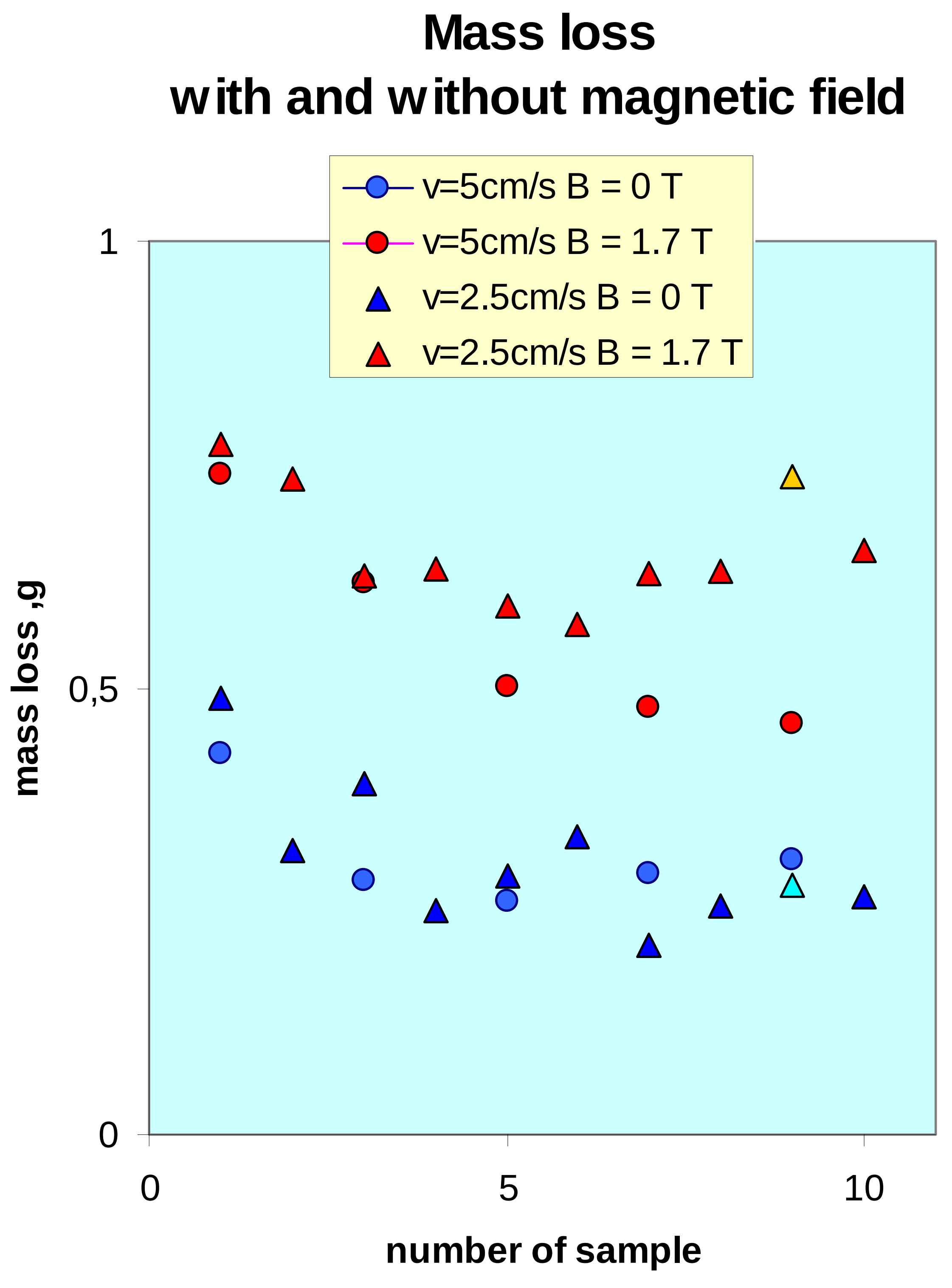
Results of influence of magnetic field on corrosion of EUROFER steel in Pb-17Li melt flow at temperature 550^0C at B = 1.7 Tesla



EUROFER steel samples located in zone out of magnetic field (B = 0)



EUROFER steel samples located in zone with magnetic field (B = 1.7 Tesla)

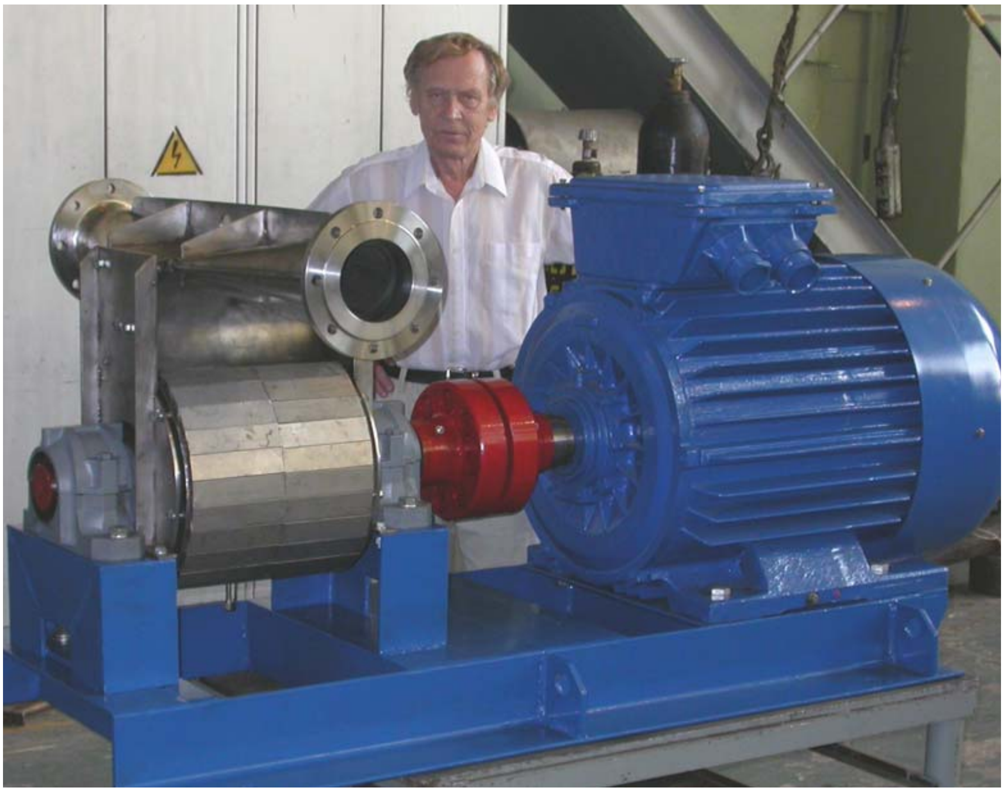


Comparison of mass losses for EUROFER steel samples located in zones without magnetic field and with magnetic field for both two experimental sessions each 2000 hours long.

3.3 EMP ON PERMANENT MAGNETS FOR ESS TARGET MODELLING

But in the frame of the given topic a discussion about the efficiency of new "non-traditional" induction machines could also be started. IPUL was invited to recommend what would be the best version of pumping the liquid metal through the target of the large, already 5MW, European Spallation Source ESS. The two target stations should be operated using mercury both as the spallating and cooling material. The temperatures are accepted in the range 20-200^{0}C.The necessary flow rate reaches 15 l/s. the corresponding pressure head 0.6 MPa.

IPUL proposed an MHD pump working on the principle of rotating permanent magnets as a good compromise between mechanical pumps and traditional induction pumps, these two initially clearly leading competitors. The idea of such induction machines is not new, but only in recent years they are starting to acquire popularity, mainly by the reason that producers of permanent magnets started to deliver products able to work at higher, interesting for liquid metals, temperatures (see chapter 2.3)



Cylindrical type EM Induction Pump on Permanent Magnets for Mercury
(operating temperature up to 200^{0}C)
Developed pressure *P* = 6 bar, provided flowrate *Q* = 13 L/s (175 kg/s)
Motor power for pump drive 90 kW

Institute of Physics, University of Latvia

WEIGHT AND COSTS EFFECTIVE HIGH EFFICIENCY
ELECTROMAGNETIC *INDUCTION PUMPS FOR LIQUID METALS*

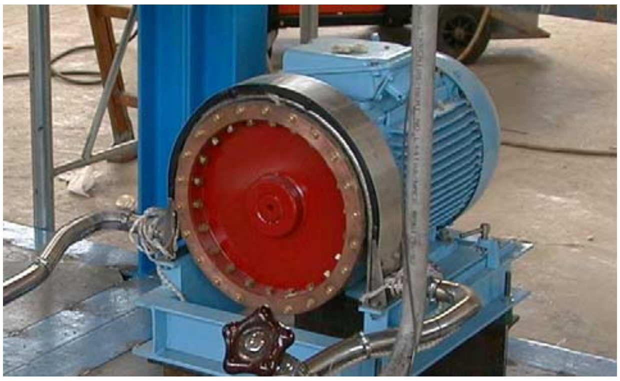


Photo of cylindrical pump (Pump No.1)

Photo of discs-type pump (Pump No. 2)

The design concept of electromagnetic induction pumps (EMIP) with permanent magnets have been developed which have many advantages in comparison with traditional 3-pase inductors. In the proposed pumps the needed alternating travelling magnetic field for inducing dragging forces in liquid metal is generated by system of rotating permanent magnets.

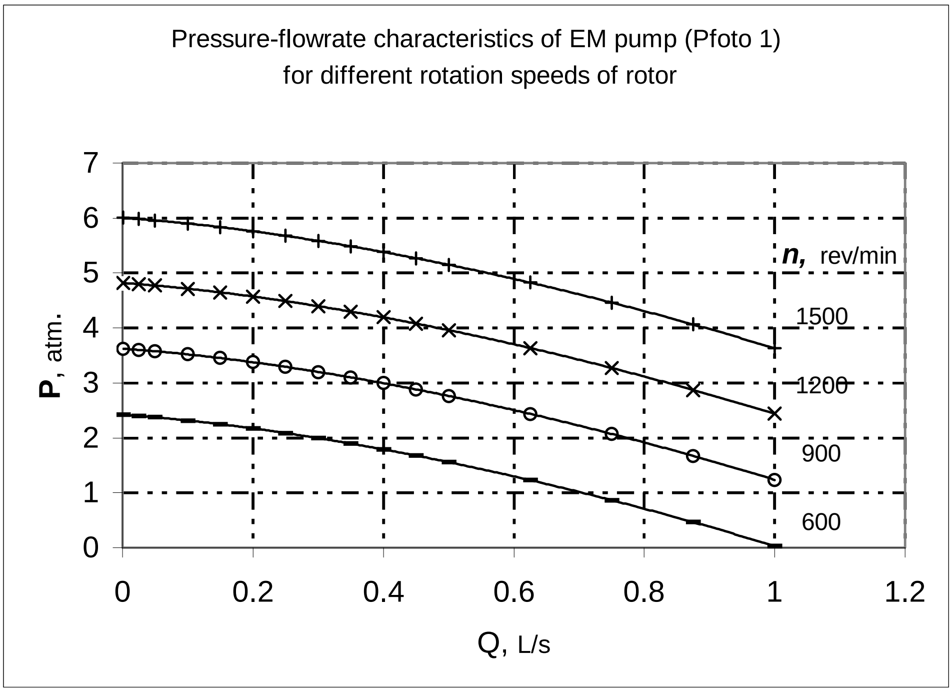
The main advantage: THERE ARE NO WINDINGS IN PUMPS AT ALL!!!
From this main advantage another important advantages follow:* no electrical isolation problems at high temperatures, simpler construction, smaller overall dimensions and weight, higher efficiency. *For feeding of traditional inductor pumps there is a need for additional rather expensive devices - 3-phase variable voltage transformers. For the driving of pumps basing on permanent magnets the standard AC motors can be used with power supply through standard frequency converter allowing to adjust needed productivity of the pump by adjusting rotation speed of motor.

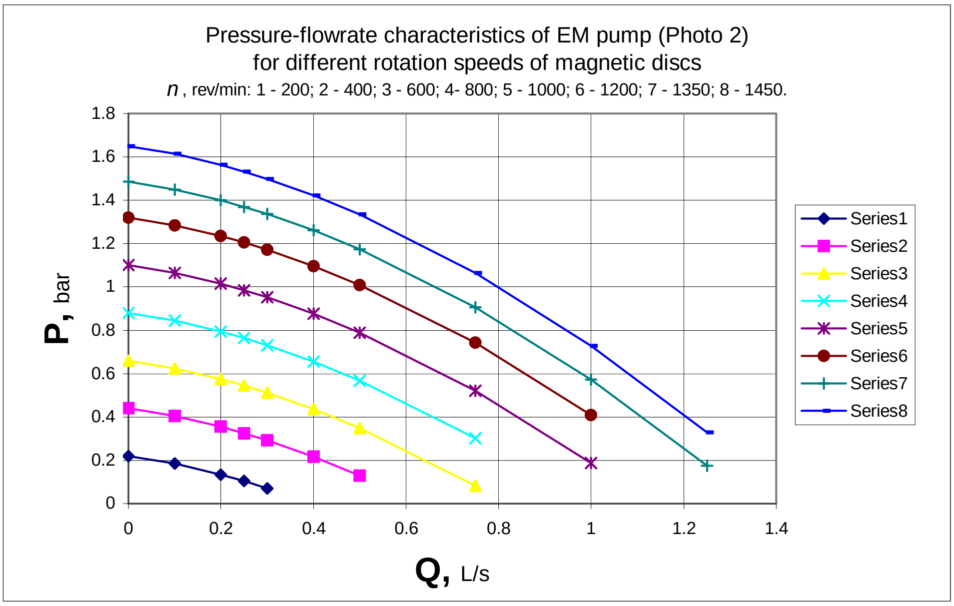
At Institute of Physics of University of Latvia many models of pumps were tested demonstrating their efficiency. Real pumps for eutectic alloy Pb-Bi at operating temperatures up to 400^{0}C have been produced and are operated successfully in liquid metal plants for studies related to development of European Neutron Spallation Sources (Italy, Switzerland). Also pumps for pure Pb have been constructed for operating temperatures up to 500^{0}C.

Such EMIP design concept of pumps can be used also in metallurgy for pumping metals having relatively low melting temperatures and high electrical conductivity, such as Al, Zn and Mg. The temperature of liquid metal being pumped may be much higher than operating temperature of magnets, as magnetic system has no contact with the walls of the channel of pump and due to rotation it can provide sufficient self-cooling by around turbulent air flows or at providing additional forced ventilation, or thermal shielding.

On fig.1 and fig.2 the P-Q characteristics (pressure-flowrate) for pumps shown on photos have been demonstrated.

Leader of the project: Dr. Phys. I.Bucenieks
Information for contacts:
Institute of Physics of University of Latvia,
Salaspils-1, Miera 32, LV-2169, LATVIA
Phone: 371.7.94.47.00; 371.6.407.570
FAX: 371.7.90.12.14; E-mail: imants@tesla.sal.lv

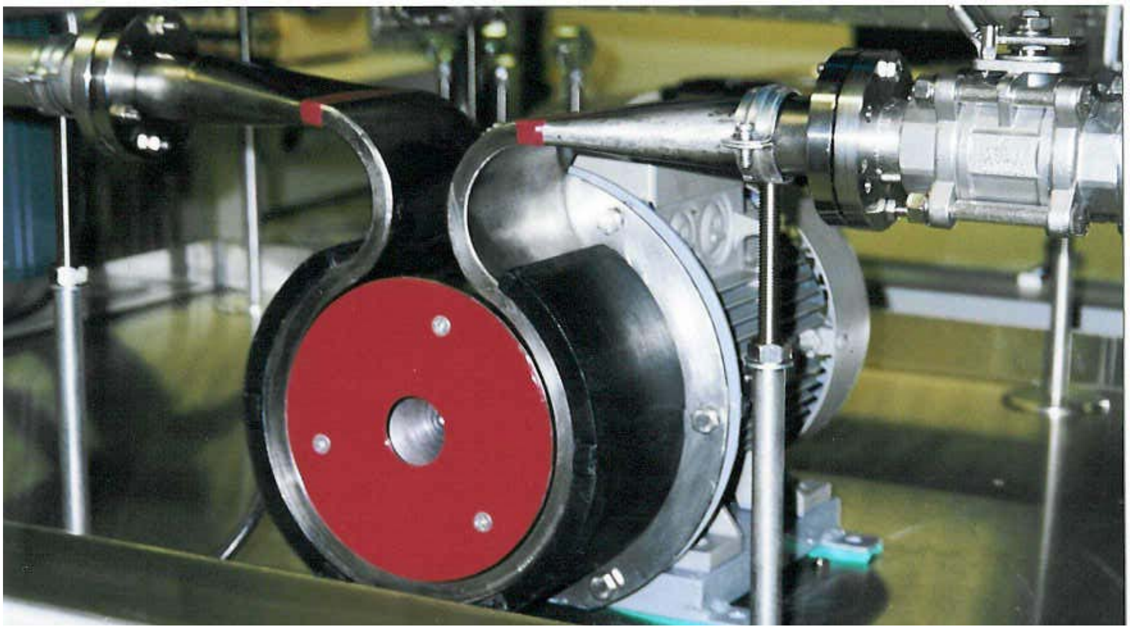




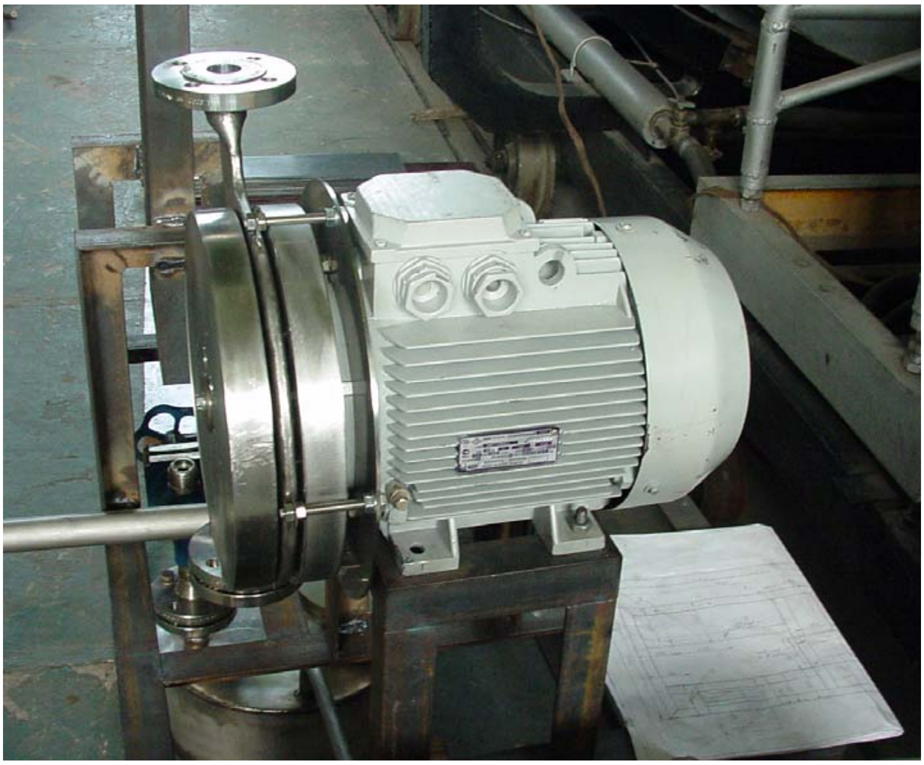
Carried out modeling experiments, calculations and gained experience show that more powerful pumps developing higher pressure and providing much bigger flowrates can be constructed basing on the same principles.

At conclusion it is worth to mention *one other important advantage* of electromagnetic induction pumps basing on permanent magnets in comparison with 3-phase linear inductors. In 3-phase inductors there are negative longitudinal end effects diminishing efficiency of pump, as at the ends of the inductor due to interference of higher harmonics not a travelling but only pulsating magnetic field is generated (as different harmonics have different travelling velocity). In pumps basing on permanent magnets all harmonics have the same velocity (defined by rotation speed of magnetic system) and so are giving positive contribution in producing the dragging electromagnetic force. So in pumps basing on permanent magnets negative longitudinal effect does not exist.

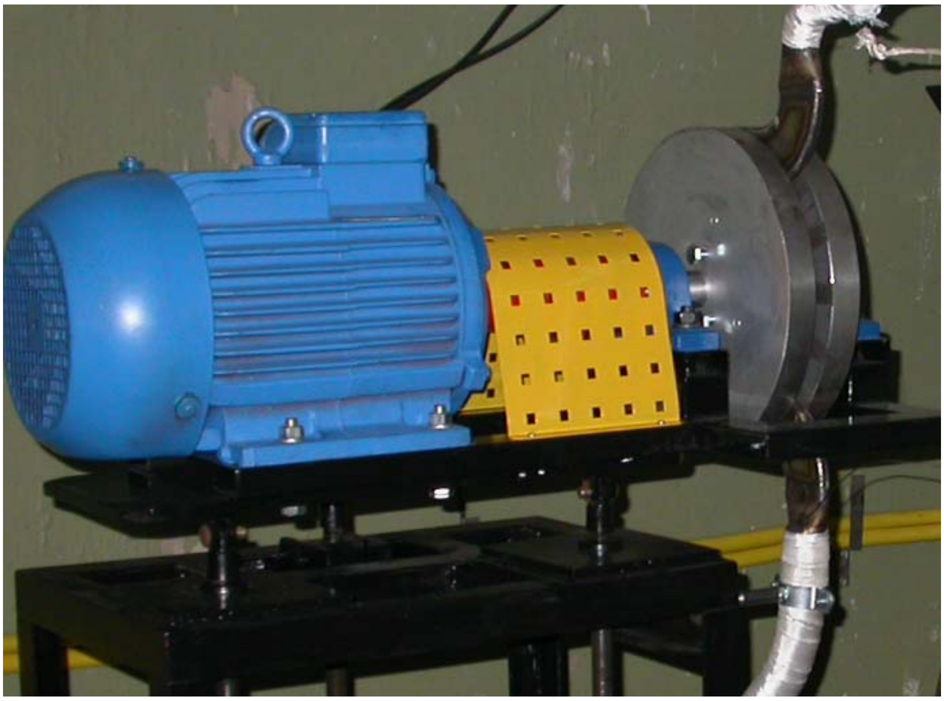
Examples of some Permanent Magnets Induction Pumps:



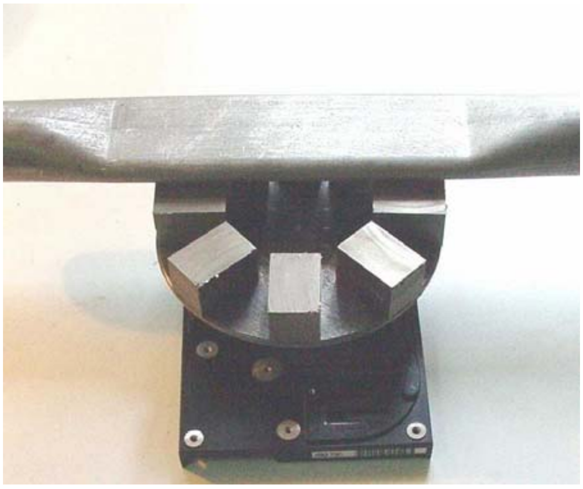
Cylindrical type EM Induction pump on Permanent Magnets
For In-Ga-Sn eutectic alloy
(developed pressure 3 bars, provided flow rate 2.5 L/s)

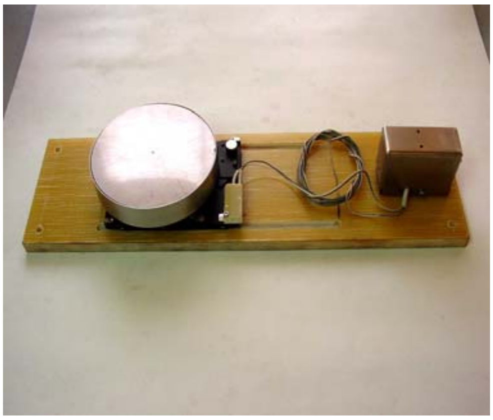


Discs type EM Induction pump on Permanent Magnets for lead (Pb)
(operating temperature 500^0C)



Electromagnetic Induction Pump on permanent magnets installed in Pb-17Li loop for long run corrosion experiments. (operating temperature 400^0C)





Electromagnetic Inductin Flowmeter on Permanent Magnets
(sensitivity of flowmeter – 0.1L/s for mercury and Pb)

3.4 TESTING OF THE LIQUID METAL LIMITER CONCEPT ON THE TOKAMAK ISTTOK

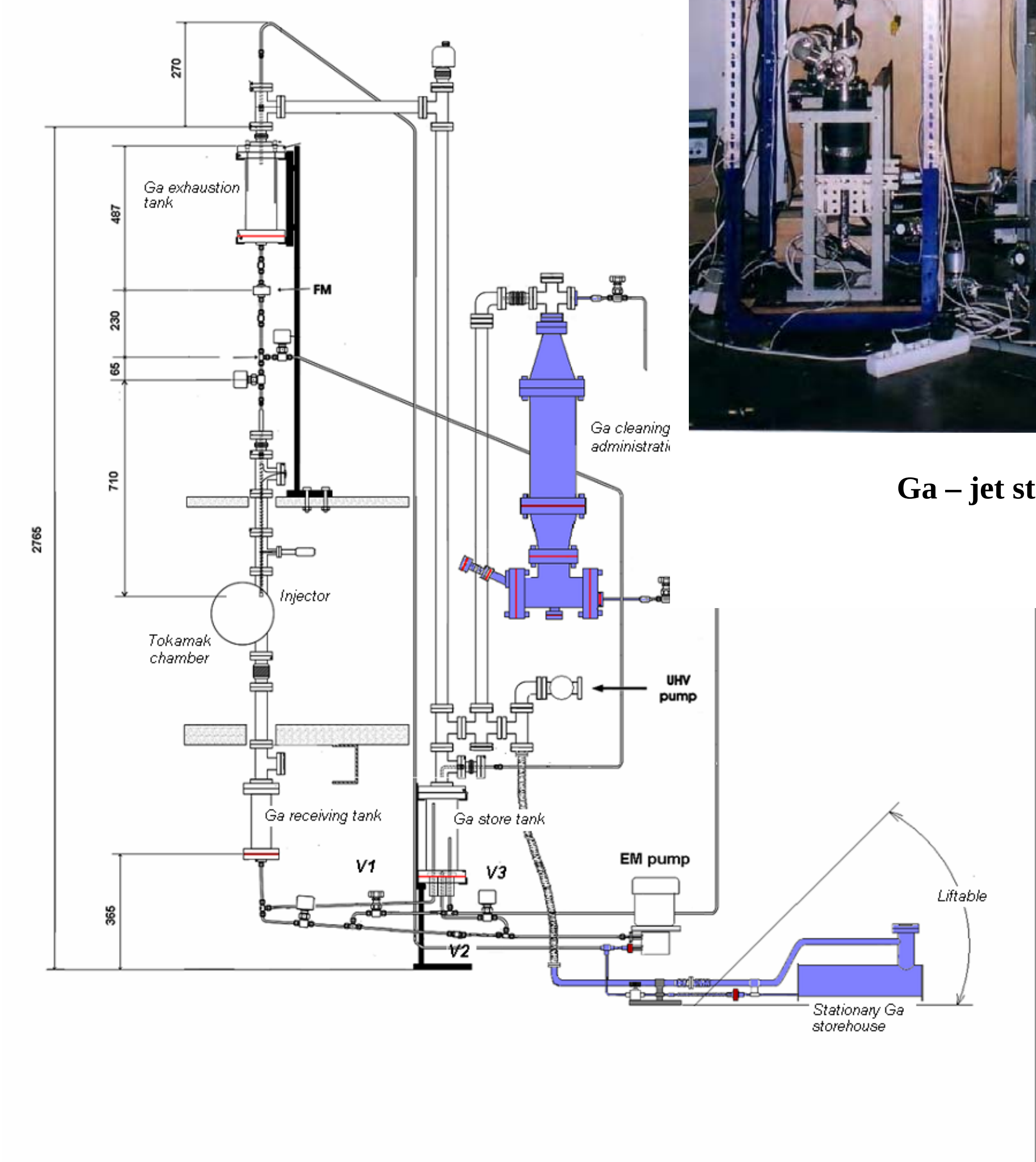
Materials currently used in large scale fusion devices are submitted to very high power loads, up to GW/m^2 during off-normal events. As a result a frequent replacement of the plasma facing components has to be expected at the present approach to the fusion research program. One way to overcome that issue, which has attracted attention in several waves both in the past as well as today, is linked to the use of liquid metals. The possibility to perform a permanent renewal of liquid surfaces has been pointed out as adequate solution for both the protection of solid walls and an power exhaustion from plasma. Among a set of several liquid metals Gallium possesses good physical properties to be compatible with fusion plasmas.

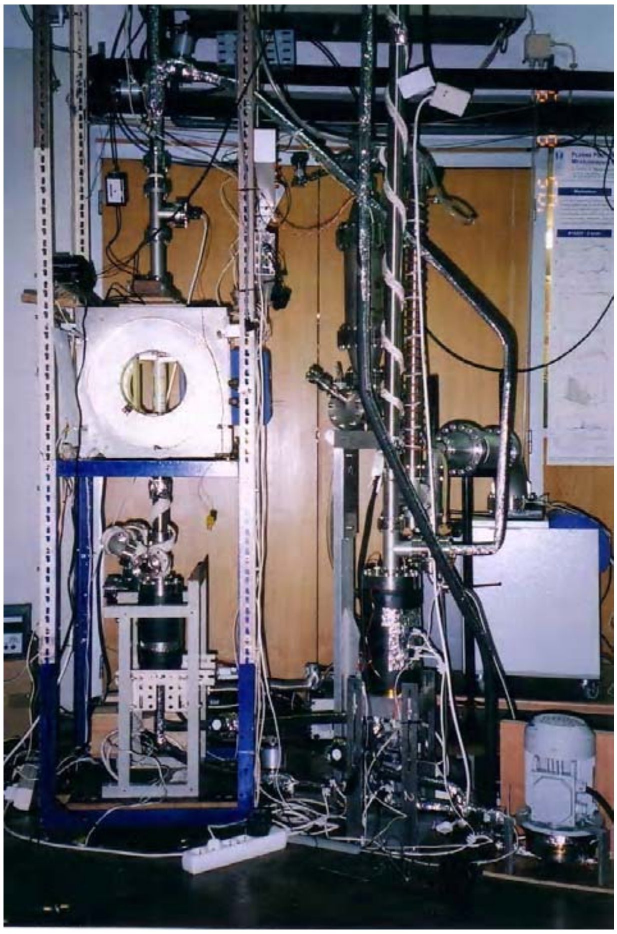
In ISTTOK (a small size tokamak with: R= 0.46 m, a= 0.085 m, B_T=0.45 T, $n_e(0)$= 5x10^{18} m^{-3}, $T_e(0)$= 200 eV, I_P~8 kA an V_{loop}~4 V) we intend to study the interaction of a liquid Gallium jet with plasmas which will be generated by hydrostatic pressure and injected in the shadow of an existing moveable stainless steel limiter. Both the jet and the limiter positions are variable allowing for a controlled exposure of the liquid Gallium to the plasma. The design of the loop has been performed so that the liquid metal will always be electrically isolated from the vacuum vessel remaining at the plasma potential.

In general, the liquid metal stand on ISTTOK could be considered as consisting of two segments. First, of a set of components responsible for key functions of the stand (vessel of hydrostatic pressure, pneumatic “on/of “valve, flowrate controlling valve, flowmeter, the injector itself with displacement screw, droplet receiver, etc). Second, of a supporting/supplying part (liquid metal reservoir, the e.m .pump, supplying tubes and valves, etc) not directly involved in the process, even not permanently in action. In Institute of Physics a modeling facility was installed (fig.2.1) directly repeating the composition of the mentioned “key part” of the stand, including the nomenclature of components. The “key elements” were ordered in duplicate, one for the stand on ISSTOK, the second for the modeling facility in Riga. Also 8 kg of gallium were received in Riga. It should be remembered that, in fact, it was the first case when liquid gallium was used as a working medium in a complicated hydraulic system, containing pump, different valves, measuring devices, etc.

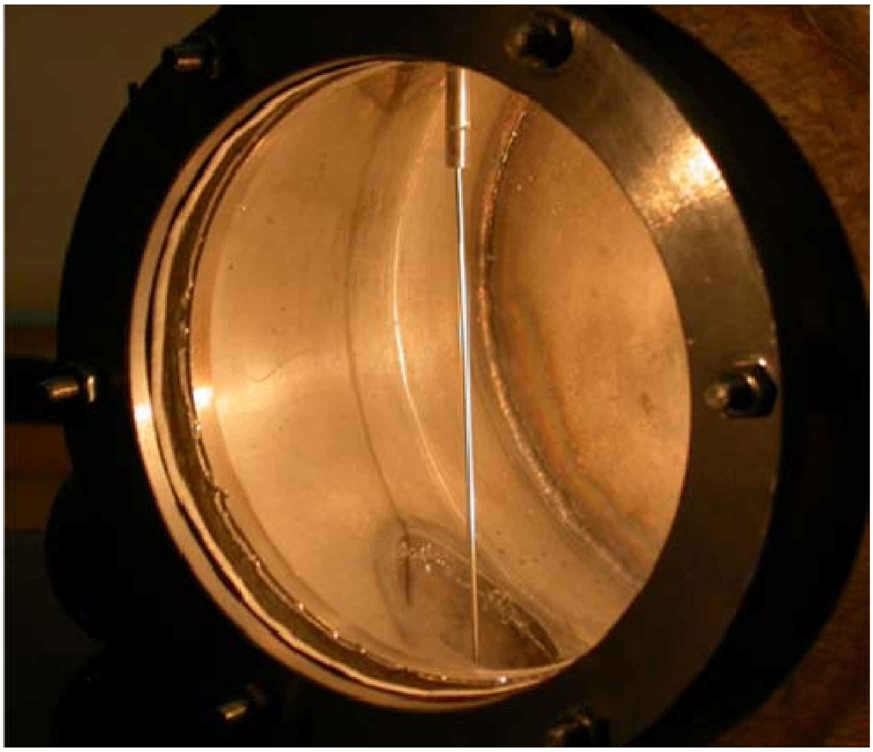
The scheme of stand and some pictures of jets are showed below.

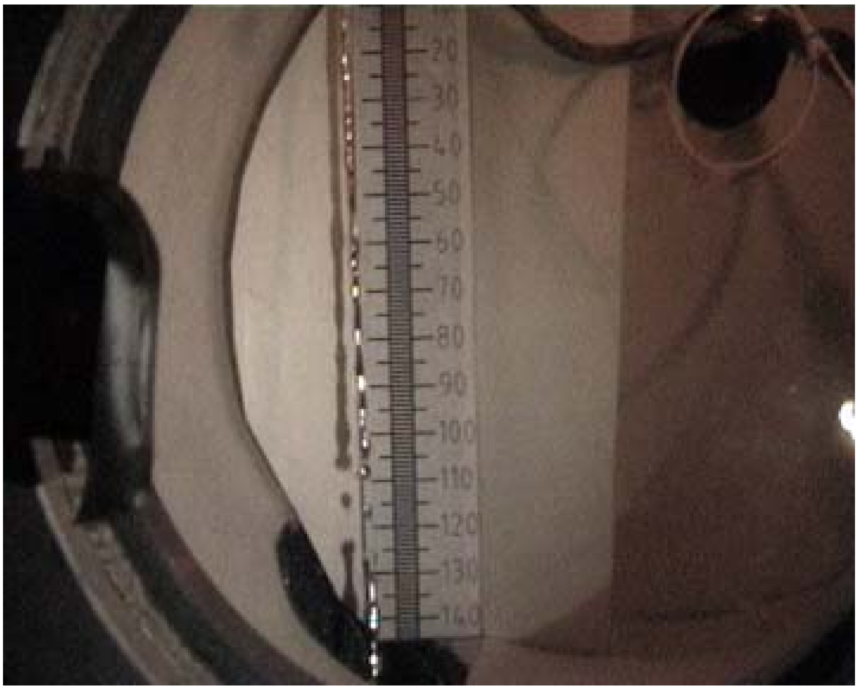
Principal scheme of the Ga-jet stand





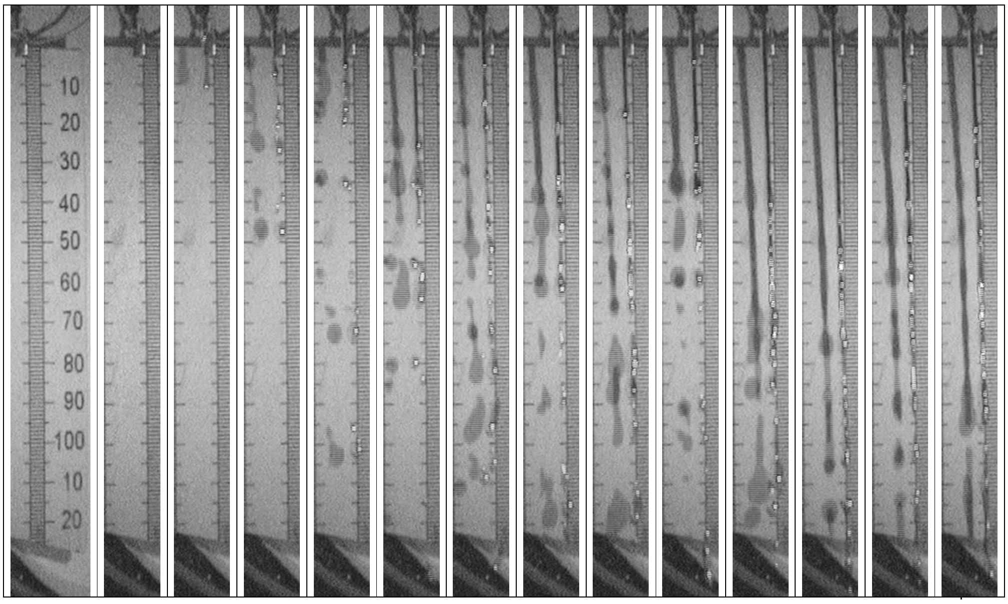
Ga – jet stand



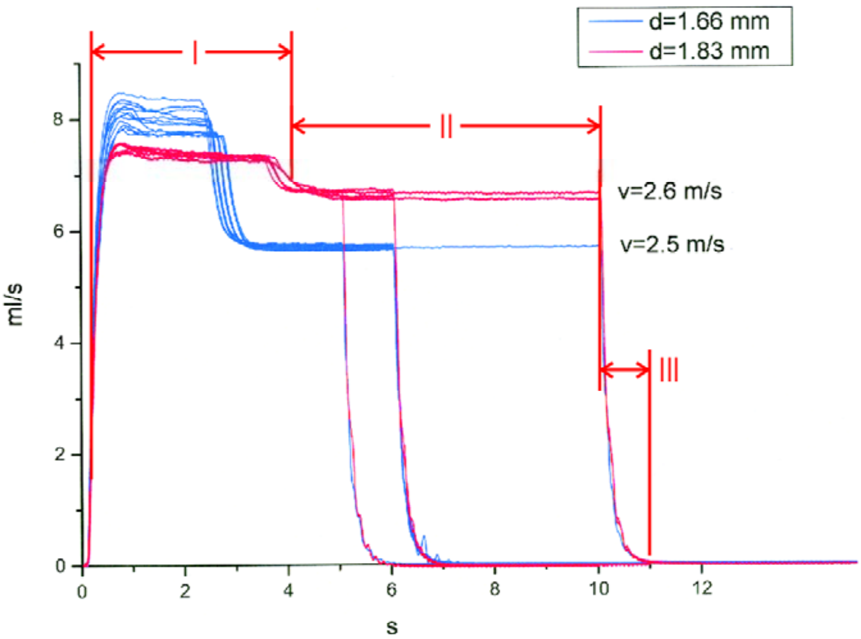


Liquid Gallum jet in the cross section of the discharge chamber at different velocity of issue. The below photo displays a phenomenon of jet disintegration (diameter of jet ∅ 2.3 mm)

Beginning of the jet issue: Δt=0.04 s, ∅ 2.3 mm, flowrate 7.5 mL/s, v=1.81 m/s



Time interval under consideration



Free phases of the process can be distinguished: 1) – filling in the injector; 2) – phase of stable jet; 3) – at the end the mentioned dropping-out phase.