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# Recent Calculations and Experiments for Liquid Metal Targets Development at PSI

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### Abstract

The development of high power neutron converters/spallation targets within the frame of in-house projects as well as within international projects for various research purposes includes the design and test of different concepts for liquid metal targets. Thermal-hydraulics and structural mechanics are employed to demonstrate that the structural integrity of the most delicate components of the target can be maintained under a variety of operational and accident-scenario conditions. It is of crucial safety importance that, for instance, the Beam Entrance Window (BEW) is adequately cooled and can sustain cyclic thermal stresses during operation of the target.

### Introduction

The development of high-power spallation and converters targets has been conducted apace at PSI driven by in-house and international projects, which demand increasing neutron production and high safety measures. A spallation reaction takes place when a high-energy proton beam impacts on a heavy target material made from lead, lead bismuth or mercury. It results in the emission of high-energy neutrons. Typically the neutron flux depends on the energy and power of the proton beam, target and coolant material and the overall geometrical configuration of the target. The high-intensity neutron beams are used in fundamental multi-discipliner scientific investigations for determining internal structures on molecular levels. The huge amount of heat deposited in the target and in the structural materials during spallation processes must be removed; heavy liquid metals, which are spallation material and also serve as a coolant is an interesting possibility to maintain the structural integrity of the target.

### 1. Conceptual Designs of Heavy Liquid Metal Target

Recently extensive computational and experimental work related with the development of a high power neutron converter target for the EURISOL (European Isotope Separation On-Line) project, supported by the European Union within the context of the 6$^{th}$ framework program for research development [1] has been accomplished by PSI in cooperation with IPUL (Institute of Physics of the University of Latvia, Latvia) and CERN (Conseil Européen pour la Recherche Nucléaire-European Organization for Nuclear Research). The conceptual design of such target is shown in Fig. 1. The proton beam penetrates into the mercury through the conical cusp window. The target fluid reverses at the beam entrance window and exits the target downstream of the main guide tube. The main features of the design was the BEW (Fig. 1b) shaped as inverted conical cusp, the flow reverser (Fig. 1b) i.e flow vanes at the target beam entrance window and near the guide tube, and the inlet section, where cold liquid metal enters the target [2]. The design was optimized using a number of 2D and 3D calculations at a constant mass flow rate of 171 kg/s, assuming uniform velocity distribution at the inlet of the beam window. Initial conceptual studies of the whole facility performed at CERN [1] showed that the total heat deposited into the target material reaches 2.3 MW under normal operation conditions. The target is about 1 m in length and 15 cm in diameter.

## 2. CFD and FEM for Heavy Liquid Metal Targets Development

During the design and construction phase of th international projects MEGAPIE (Megawatt Pilot Experiment) and EURISOL (European Isotope Separation On-Line Facility) the Computational Fluid Design (CFD) was considered as a useful tool and used extensively for optimisation of thermal-hydraulic behavior of the lower section of the liquid-metal container [3], full liquid metal target [2] and for post analysis of the target during transients [4]. Such application field for CFD draws considerable scientific interest and efforts that comprised modelling of turbulent momentum and heat transfer, especially for heavy liquid metal flows as well as development of instrumentation for thermal-hydraulic and monitoring applications.

The design of above mention targets have been exclusively conducted by using standard commercial codes such as CFX, FLUENT and STAR-CD with incorporated standard Reynolds Averaged Navier-Stokes (RANS) equations with the high Reynolds number $k$–ε models. LES (Large Eddy Simulation) methods have been extensively used during design of the EURISOL converter target. In order to illustrate the methods and procedures used during the target design studies of the Target Development Group (TDG), the following example is shown.

## 3. EURISOL Converter Target: Harmonic Response Analysis (Coupling LES and FEM)

An example of the instantaneous velocity field obtained by LES is shown in Fig. 1a. Sources of instabilities, which may cause structural resonances, are clearly marked by arrows and capital letters in the figure. The effects of the flow vanes on the overall resonance of the target structure were investigated by the one–way coupled frequency response analysis. Namely, the structural model (Fig. 1b) was run in a sine sweep mode with an excitation load frequency range between 10 and 150 Hz by using the amplitudes of the spatial pressure distribution extracted from the LES calculations. The hull tip displacement obtained from such analysis (Fig. 1c,d) showed the existence of resonance frequencies between 35 and 50 Hz, though the energy content was relatively low (displacement of the hull tip was only 0.05 mm). The flow vanes are subjected to far higher dynamic loads, where load peaks are located on welding positions. Due to the high stress amplitudes and frequencies the flow vanes may undergo a high-cycle fatigue [2]. In light of the prediction, adequate safety precautions were taken to guard against adverse consequences and the team was thus able to conduct the final test carefully until the rupture of the flow reverser.

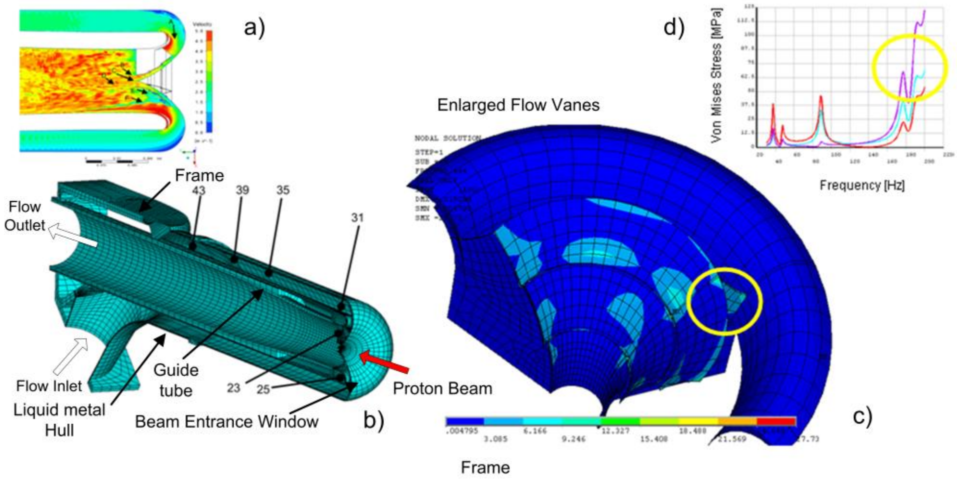


Fig. 1. a) LES calculation [2], [6] showing an instantaneous velocity field. Large eddy structures and sources of instabilities are marked by arrows and capital letters. LES computed pressure variations at representative points are applied to the FEM structural model (b) by extraction of modal content from Fast Fourier Transform (FFT) processing of the pressure, which, when run in a sine-sweep frequency response analysis, gives displacements on all points of the structural model; the hull tip (c) displacement is shown on right (d)

## 4. Experiments for Heavy Liquid Metal Targets Development

In order to test the feasibility of using the initial and final configurations chosen to solve the complex cooling requirements, to investigate various coupled fluid-structural phenomena, to calibrate and test instrumentation and to provide data for code validation various small- and large-scale experimental installations with water and liquid metal as working fluids have been developed. In the following sections some of the most interesting experimental results conducted over past several years by the TDG group are selected to demonstrate the developed procedure for components testing and to present important findings.

### *4. 1. LIMET (Liquid Metal Target Test Bed)*

As the most delicate component of the lower target container is the Beam Entrance Window (BEW) (Fig. 2), it is necessary to demonstrate that the structural integrity of the window would be maintained under a variety of operational and accident-scenario conditions. In the actual MEGAPIE design [3] unidirectional flow across the window was affected by a jet exiting from a bypass nozzle in order to provide adequate window cooling. As the use of an additional bypass pump increases significantly the complexity and costs of the system, the idea of having a reliable configuration without additional bypass flow directed the design efforts. Therefore, the main motivation for undertaking further research activities is to find a lower target design with a BEW that would be adequately cooled only by the main flow. Generally two experimental investigations have been planned: LIMETW with water and LIMETLBE with LBE as a working fluid. A goal of the water experiments (LIMETW) is to investigate several configurations of the riser tube end geometries that should provide adequate cooling of the BEW. Only concepts of “promising” geometries are to be subsequently investigated during the second session LIMETLBE.

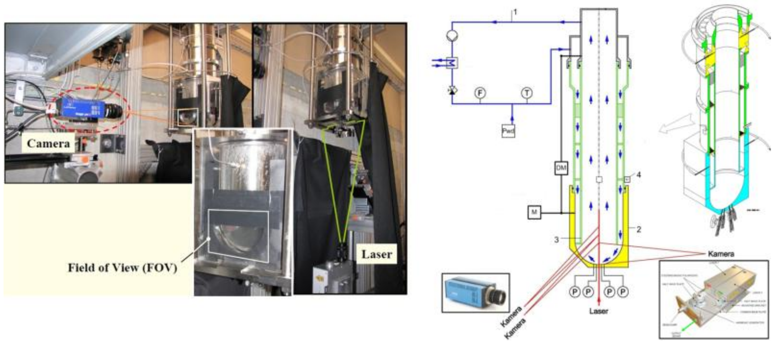


Fig. 2. Target mock-up with PIV experimental set-up

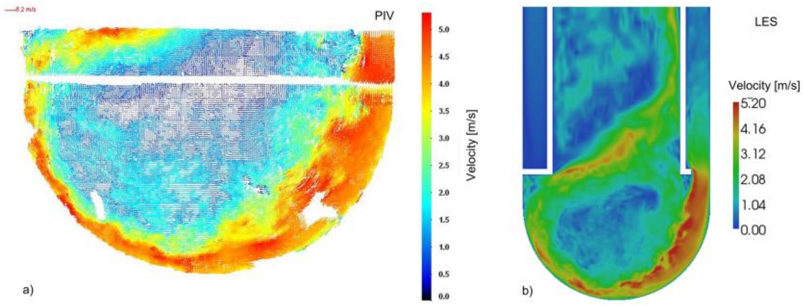


Fig. 3. Scalar maps [5] of the a) PIV instantaneous velocity field (2 velocity components) and b) LES instantaneous velocity field (3 velocity components). Total liquid flow rate is 5 l/s

Stagnation regions as well as the jet region near the BEW are well resolved by LES by using the standard code settings. Both LES and PIV 2D instantaneous fields reveal instabilities in the shear layer, which may cause fluid-induced vibrations of the riser end. Results clearly show that such target configuration is not promising as large recirculation areas exist.

***4. 2. METEX (Mercury Target Experiment)***

The main goal of experimental sessions METEX 1 and METEX 2 (Fig. 4) [6] was to investigate the hydraulic and structural behavior of the EURISOL target mock-up under various flow conditions and for two flow configurations (without and with flow vanes), to provide experimental data for code validation and to test various sensors and remote monitoring techniques which are to be used for accurate predictions of the system health during real target operation.

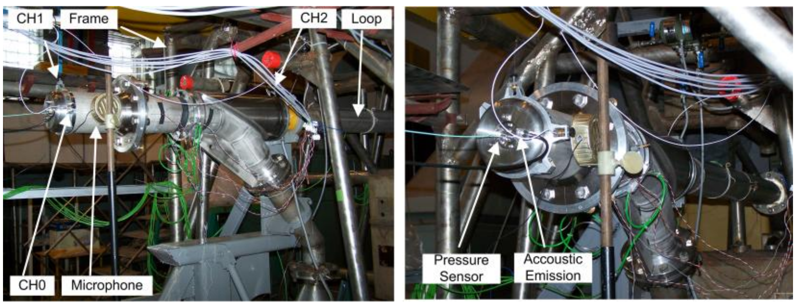


Fig. 4. The EURISOL target mock-up equipped with sensors was connected to the IPUL liquid metal loop

High-speed pressure measurements, obtained during the METEX experiment, have been chosen as an example. Flow pulsations generated by the electromagnetic pump affected all measurements, which can be seen in power spectra, especially when the signal-to-noise ratio is high. Due to the high-level electromagnetic noise in the laboratory, the high-speed pressure measurements were strongly affected by the 100 Hz pump-induced component and its harmonic descendants starting from 50 Hz (the power spectrum that proves this fact is not shown here). The amplitude of fluctuation for the non filtered signal is ±0.25bar. For filtered pressure measurements with frequencies less than 40Hz the amplitude of fluctuation is equal to ±0.02bar (see Fig. 5).

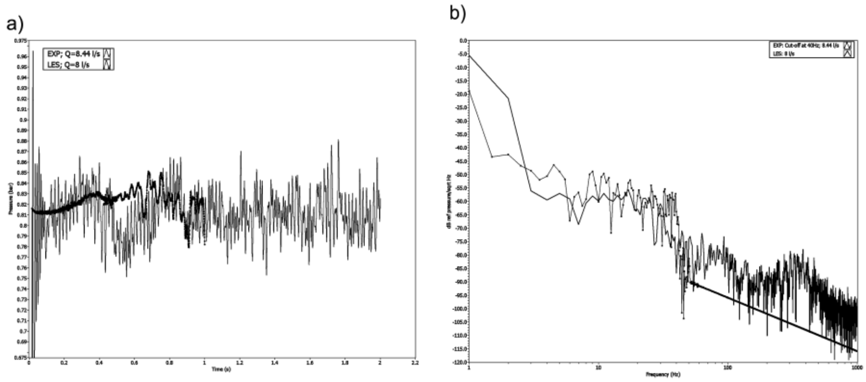


Fig. 5. Filtered pressure fluctuations around a mean value for 8 l/s: a) comparison with LES [7], b) comparisons of power spectra, which shows the cut-off frequency

The comparison shown in Fig. 5 demonstrates that low frequencies of less than 40Hz, which correspond to large eddy structures, are not perturbed by the pump effect and it is reasonable to filter the experimental data accordingly and then to compare them with LES-CFX simulations. The frequencies created in the flow by the electromagnetic pump and the noise sources are above 50Hz.

***4. 5. COOLWETT-Heat Transfer Measurements for various Wetting Conditions***

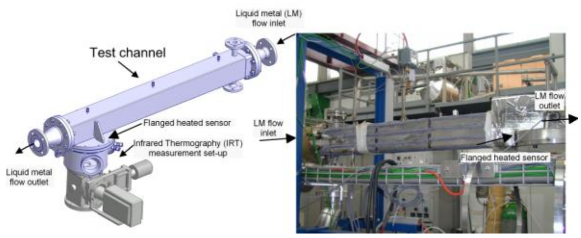


Fig. 6. COOLWETT experimental section: model (left) and installation (right)

In order to sufficiently cool the BEW of high power heavy liquid metal targets high liquid metal velocities are needed as predicted by computational studies. For example, 1 m/s of Lead Bismuth Eutectic near surfaces (LBE) for operated 1 MW MEGAPIE target at PSI or 2 m/s of mercury for the planned 4 MW EURISOL target at CERN. Since high velocity- and high temperature-induced corrosion-erosion problems may affect the life time of the BEW, spraying of an additional several micrometers thick protective layer of special materials could be the solution. On the other side, such layer may affect the surface wetting and, therefore, influence convective liquid metal heat transfer. In order to study these effects, the experimental investigation of liquid metal heat transfer in a horizontal, square channel with uniform wall heat flux is currently performed on an adopted PSI LBE loop. The main goal of this experiment is to study the effect of the surface treatment on the heat transfer coefficient in fully-developed liquid metal flow. The heat transfer measurements are done Infrared Thermography (IRT).

## Conclusions

During last years extensive computational and experimental work related with development of the high power spallation and converter targets have been conducted at TDG-PSI group in the field of thermal-hydraulics and structural mechanics. The research activities were driven by various in-house and international projects. Several small and large scale experimental facilities equipped with modern data acquisition systems, measurement techniques and instrumentation have been developed, constructed and built. Some of the most interesting results and experimental set-ups, which are presented in this paper, reflect and highlight the importance of continuous target development activities conducted by TDG, especially regarding reliability and safety issues related in the design and operation of facilities with high power targets.

## Acknowledgement

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## References

[1] Blumenfeld, Y., Fortuna, G.: *Final Report of the Eurisol Design Study (2005-2009).* European Commission Contract No. 515768 RIDS, published by GANIL France, www.eurisol.org, 2009.

[2] Samec, K., Milenković, R., Dementjevs, S., Ashrafi-Nik, M., Kalt, A.: *Design of a compact high-power neutron source-The EURISOL converter target*. Nuclear Instruments and Methods in Physics Research A, Vol. 606, 2009, pp. 281-290.

[3] Dury, T.: *CFD design support at PSI for the international MEGAPIE liquid-metal spallation target*. Journal of nuclear science and technology, Vol. 41, 2004, No. 3, pp. 285-295.

[4] Smith, B. L., Leung, W., Zucchini, A.: *Coupled fluid/structure analysis of the MEGAPIE spallation source target during transients*. Nuclear Engineering and Design, Vol. 237, 2007, pp. 1656-1667.

[5] Dementjevs, S., Milenković, R., Geza, V., Barbagallo, F., Joray, S., Kapulla, R., Kalt, A., Manfrin, E., Patorski, J., Wohlmuther, M.: *LIMET- A test bed for liquid metal targets.* ICANS XIX, 19th Meeting on Collaboration of Advanced Neutron Sources, Grindelwald, Switzerland, March 8 – 12, 2010.

[6] Milenkovic, R., Dementjevs, S., Samec, K., Platacis, E., Zik, A., Flerov, A., Thomsen, K.: *Structural-hydraulic liquid metal test of the EURISOL target mock-up*. Nuclear Instruments and Methods in Physics Research Section A, Vol. 607, 2009, Issue 2, pp. 279-292.

[7] Samec, K., Milenković, R., Blumenfeld, L., *Computational fluid dynamic analysis of turbulent liquid metal flow in EURISOL target mock-up*. Submitted to Nuclear Instruments and Methods in Physics Research Section A, 2010.

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