XT-ADS WINDOWLESS SPALLATION TARGET DESIGN AND CORRESPONDING R&D TOPICS

A. Guertin, N. Thiollière, A. Cadiou, J.M. Buhour, O. Batrak
Laboratoire SUBATECH, CNRS/IN2P3-EMN-Université, F-44307 Nantes, France

M. Dierckx, J. Heyse, K. Rosseel, P. Schuurmans, K. Van Tichelen
SCK•CEN, Boeretang 200, B-2400 Mol, Belgium

R. Stieglitz, A. Batta, A. Class
Forschungszentrum Karlsruhe, P.O. Box 3640, D-76021 Karlsruhe, Germany

F. Roelofs, V.R. Gopala
NRG Petten, Westerduinweg 3, P.O. Box 25, NL-1755 ZG Petten, The Netherlands

H. Jeanmart
UCL, Louvain la Neuve, Belgium

V. Moreau
CRS4, Polaris Edificio 1 CP25, 09010 Pula (CA), Italy

Abstract

The objective of the European 6th framework Integrated Project (IP) EUROTRANS (EURopean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System) is to demonstrate the feasibility of transmutation of high level nuclear waste using sub-critical Accelerator Driven Systems (ADS). In the framework of the IP EUROTRANS that has started in April 2005, the XT-ADS (eXperimental demonstration of Transmutation in an Accelerator Driven System) reference design with LBE (Lead-Bismuth Eutectic) cooling is developed in a detailed manner amongst others to prove the feasibility of windowless spallation target. Studies have been done making maximum use of the existing work for defining the needed complementary work in terms of design, thermal-hydraulics or neutronic and nuclear assessment. In this document the present status of the design of a windowless spallation target for the XT-ADS and the status of corresponding R&D topics are discussed.

Introduction

The Integrated Project EUROTRANS within the ongoing EURATOM 6th European Commission Framework Programme is devoted to the study of transmutation of high-level waste. The work is focused on transmutation in an Accelerator Driven System.

The XT-ADS is to be built and tested in a near future. The machine should fulfil three objectives:
- demonstrate the ADS concept (coupling of accelerator, spallation target and sub-critical core) and its operability,
- demonstrate the transmutation of a sizeable amount of waste,
- provide an irradiation facility for the testing of different EFIT (European Facility for Industrial Transmutation) components (samples, fuel pin, fuel assembly …).

At the heart of the XT-ADS is the spallation target which provides the primary neutrons that are multiplied in the surrounding sub-critical nuclear core. The design of this spallation target is the key issue of the work package 1.4 of EUROTRANS. The MYRRHA spallation target module has served as the starting point for the target design of the XT-ADS [1].

After the definition of the design boundary conditions, the general layout of the spallation target loop is presented. Then the different design support studies that have been performed are described. In the last section some conclusions are formulated.

Spallation target boundary conditions

XT-ADS spallation target system has been designed to be compatible with the remote handling scheme envisaged for the entire XT-ADS. The full loop can be removed from the main vessel after unloading of the core. All active elements are placed in a separate sub-unit which allows servicing of these parts without removal of the spallation loop. The closed outer housing allows regular (yearly) replacement of the spallation target zone that will be required because of radiation induced embrittlement.

The main characteristics have been defined to get a flexible testing facility. Very compact target geometry has been settled to achieve sufficiently high neutron flux levels ($\phi_{Tot} \approx 3.10^{15}$ n/cm².s). The target space is created by removing three of the hexagonal fuel assemblies in the centre of the core [2] as it is shown on figure 1-a and 1-b.

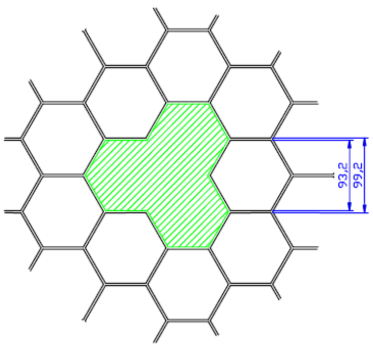

Fig. 1-a: Three assemblies in the centre of the core are removed to make room for the spallation module (dimensions in mm).

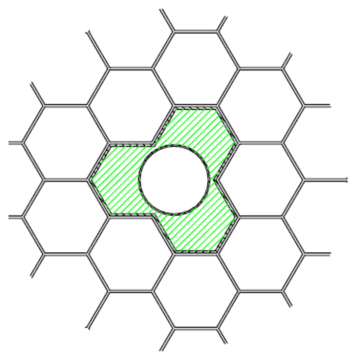

Fig. 1-b: The hashed area indicates the space available for the LBE feeder line; the inner circle indicates the space available for the proton beam.

The needed high power proton beam, several hundreds of MeV at few mA (600 MeV and 3 mA in the reference design), is delivered by an accelerator. For the accelerator part of the system, we opt for a LINAC solution. The main reason for that choice is the improvement of beam reliability at such levels of proton energy. The beam ingress is foreseen from the top of the vessel. One of the major reasons for that choice is strongly related the choice made for the target unit interface. The interface being windowless, interlinking the core with an off-axis housing for all active components, beam ingress from the bottom becomes simply unfeasible (having a penetration at the bottom of the reactor vessel is of course unsuitable).

In the figure 2-a and 2-b, the global geometrical boundary conditions of the XT-ADS spallation loop and its interference with the core are shown.

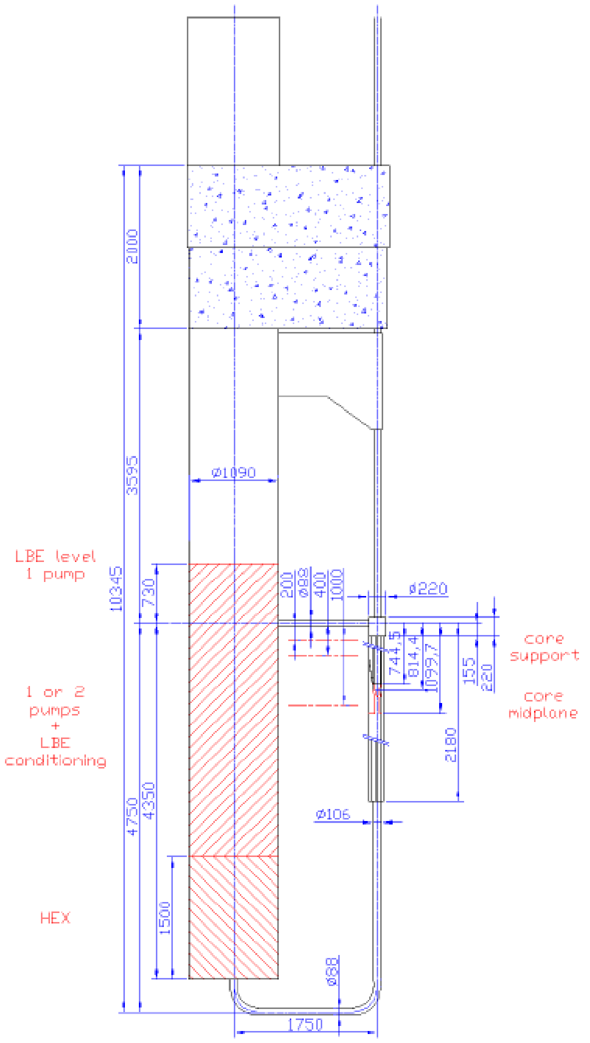

Fig. 2-a: Global geometrical boundary conditions (outer dimensions) of the XT-ADS spallation loop.

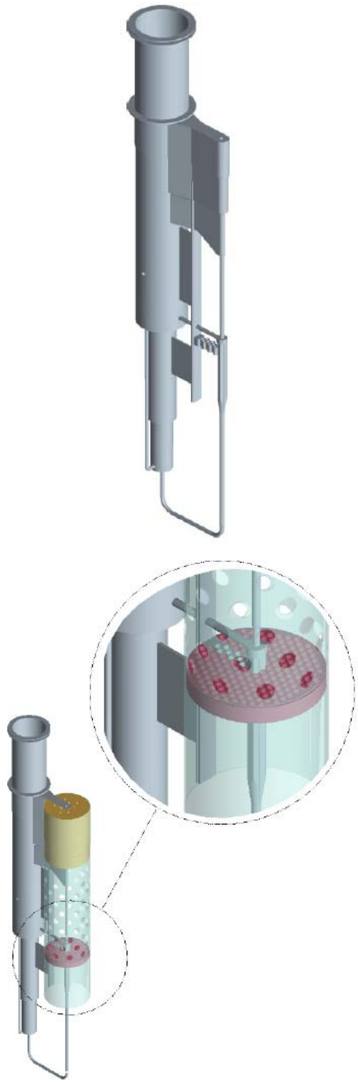

Fig. 2-b: Spallation loop general view (upper part) and interference of the spallation loop with the core (lower part).

This reliability requirement is essentially related to the number of allowable beam trips, because, frequently repeated, they can significantly damage the reactor structures, the target or the fuel, and also decrease the plant availability. Therefore, beam trips in excess of one second duration should not occur more frequently than five per year.

The total power level of the XT-ADS will be ranging between 50 and 70 MW_{th}.

A replacement of the spallation target, within the envisaged lifetime of the XT-ADS, is unavoidable. This operation should not be required too often. Spallation target unit should be able to survive operation within the ADS system for a sufficient amount of time (roughly one year).

The limited space available in the core and the high proton current lead to very high proton beam densities in the range of 150 $\mu A/cm^2$. No structural material is expected to withstand these conditions at elevated temperatures during a reasonable lifetime of the spallation target. That's why spallation target is being designed without a hot window between the target area and the vacuum of the beam line.

Spallation loop layout

The off-axis design of the spallation loop (figure 3) leaves the top and bottom of the sub-critical core accessible for fuel manipulations and the installation of irradiation experiments [3]. In addition the main part of the spallation loop is moved away from the high radiation zone which is beneficial for its lifetime.

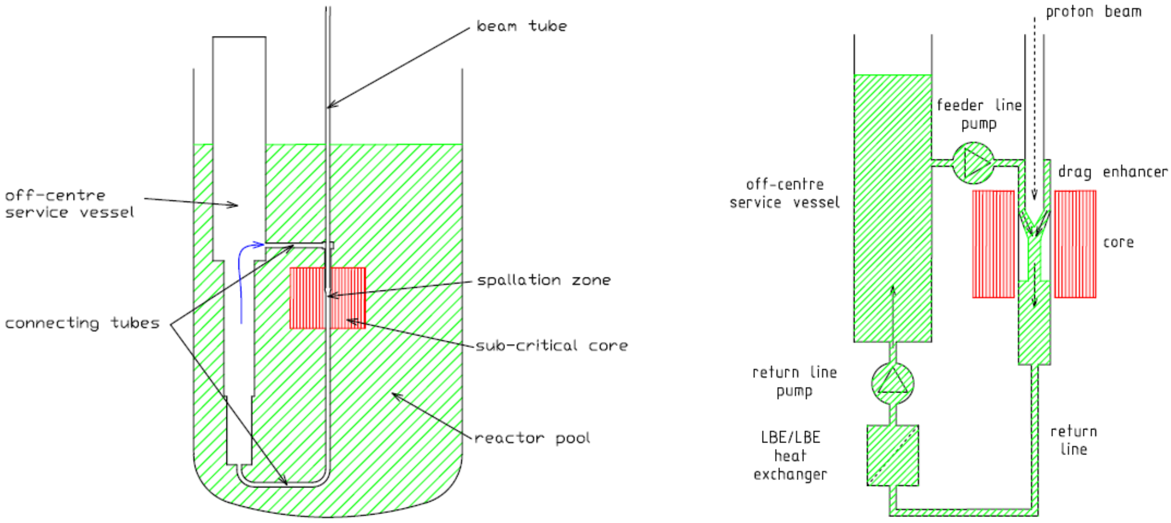

Fig. 3: General layout showing how the spallation target is split up in a centre and an off-centre part and how the two parts are connected. Hashed area figures LBE (coolant) [left side]. Schematics of the spallation loop. Hashed area figures LBE (spallation material) [right side].

Free surface and recirculation zone

The limited space to implement the target is responsible of the choice of a vertical confluent flow as formation mechanism for the target free surface. The liquid LBE is fed to the target nozzle via a vertical three-lobed annular pipe to optimise the use of the available space in the core. Target nozzle itself is designed to ensure a stable free surface flow.

A firm control over the size of the recirculation zone, formed in the centre of the target free surface, is essential.

When the recirculation zone is too small, LBE droplets are ejected from the LBE confluent zone that may cause metal evaporation when hit by the beam. If the recirculation zone is too large, it will be directly heated by the proton beam causing the temperatures to increase very rapidly which would also lead to excessive evaporation of LBE and other volatiles.

LBE as coolant and target material

The use of LBE as core coolant allows lower working temperatures than foreseen in the lead-cooled EFIT. Liquid LBE is also used for target material as forced convection cooling is required due to the thermal energy deposited by the proton beam, both circuits are separated.

In order to limit LBE evaporation and corrosion of structural materials in the target loop, the maximal temperature allowed in the target is set at about 430°C. The lower limit of the LBE flow rate is determined by this value. Because the spallation target material is cooled against the main vessel coolant, the lowest achievable temperature during normal operation of 330°C is mainly determined by the inlet temperature of the core, 300°C.

Pumping options

The free surface level is particularly difficult to maintain under the dynamic changes caused by beam trips and during the start-up / shut-down procedures. In order to cope with these dynamics, an extra free surface is created just below the target zone. This extra free surface will act as buffer and stabilizes the target format process. The main pump lifts the LBE that has passed the heat exchanger to the level of the second free surface. From here, the LBE flows through the feeder-line to the target nozzle by gravity.

The vertical flow in the feeder line just above the target is equipped with a drag enhancing structure, exceeding the minimum drag of 1 bar/m necessary to compensate for the hydrostatic pressure, to prevent the LBE to tear apart in the feeder line and reaching the target zone in free fall.

Several options still exist on the pumping strategy of the spallation loop [4]. One choice is one pump in the return line and one smaller pump in the feeder line. The feeder pump is only required to compensate for changes in friction losses in the feeder line. If these changes in friction losses prove to be acceptable or if they can be compensated in another way it may be possible to completely remove the feeder pump from the design. This will decrease the complexity of the system thus making the system not only cheaper and easier to produce but also more reliable.

Due to lack of experimental validation, in particular for the pressure loss, it was proposed to go for the conservative option of having two pumps in the spallation loop: one big main pump in the return line; one small pump in the feeder line will be used to counteract erosion/corrosion effects.

Vacuum system

The vacuum system has two essential functions:

- The pressure directly above the spallation target should be below the 10^{-3} – 10^{-4} mbar range to guarantee compatibility with the vacuum of the proton beam line and to avoid plasma formation caused by the interaction between the rest gas above the target and the proton beam.
- The confinement of volatile radioactive spallation products should be guaranteed. The vacuum system is equipped with a closed back end composed of sorption and getter pumps from where they can be batch-wise removed.

The large second free LBE surface in the servicing vessel (figure 3), directly underneath the main vacuum pumps, minimises emanation of spallation products into the proton beam line.

Design support studies

MHD pump definition

A sizing of a 13 l/s – 4 bar EMP, for the return line, has been done [5]. Within this report the general electro-magnetic pump design requirements are de-scribed as well as the principle design of the MHD pump acting as a long term regulator in the return line. Based on design requirements the pump is designed, the nominal operating point of the pump is calculated together with the efficiency and other electro-magnetic parameters relevant for the following power balance of the pump.

This pump could be designed and technically realized as cylindrical electromagnetic pump with overall dimensions of 0.6m in diameter and 2m long (see figure 4).

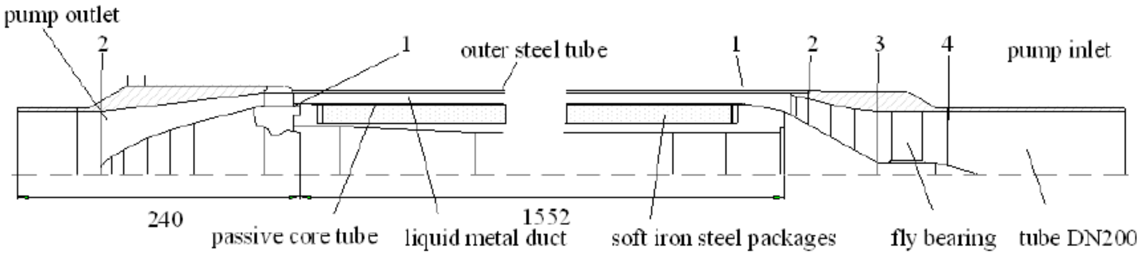

Fig. 4: Design sketch of the biggest MHD pump in the spallation target loop.

A 4 bar EMP is able to deliver the maximally needed pressure head in a one pump scenario in transient conditions. In case of a two pumps scenario, this maximal pressure head can be distributed in a nominal pressure head of 2.5 bars for the return pump and a transient head of 1.5 bars for the feeder pump. In this case, we estimate that the return pump may be designed and technically realized in overall dimensions ø 0.4 x 1m. It can be noticed that the feeding pump is smaller due to the fact that the driving pressure is even lower.

Target nozzle

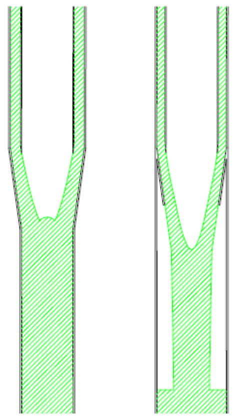

Fig. 5: Two different nozzle principles left: without flow detachment; right: with flow detachment.

Water flow mock-up experiments performed at the Université Catholique de Louvain (UCL) have shown that a more stable flow is achieved if some detachment of the LBE flow is allowed. Further experiments with LBE at the KALLA laboratory of the Karlsruhe Institute of Technology (KIT) are planned to confirm the observations made in the water loop.

The feasibility of a target nozzle that explicitly forces flow detachment is studied. Two principally different nozzle layouts are studied (figure 5). They are different by the fact that in the left nozzle the LBE flow is designed to be in contact with the walls at all times, while the right nozzle is designed to have the LBE flow separate from the walls and form a free falling jet.

Due to its inherent stability the nozzle with flow detachment is chosen to be the reference design for further target development [2].

At this stage, the current hydraulic design of the target area of the XT-ADS spallation loop is shown in the figure 6-a below.

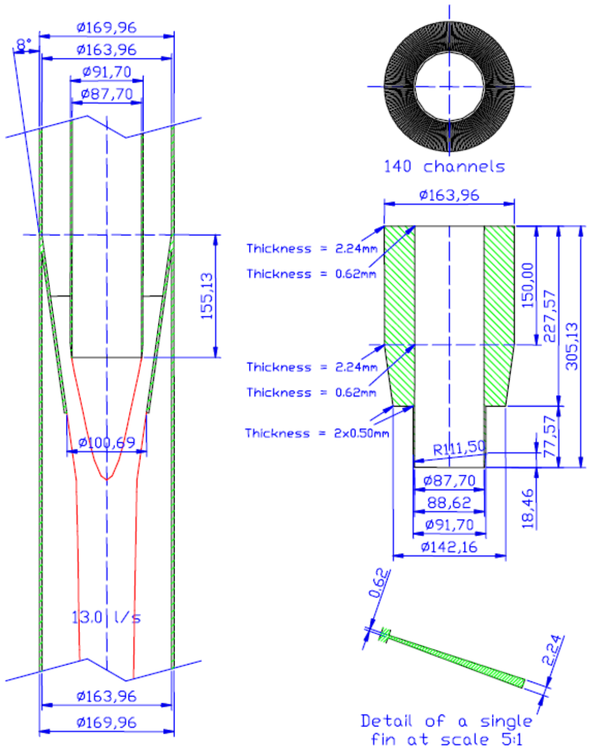

Fig. 6-a: XT-ADS nozzle design called v0.10LBE.

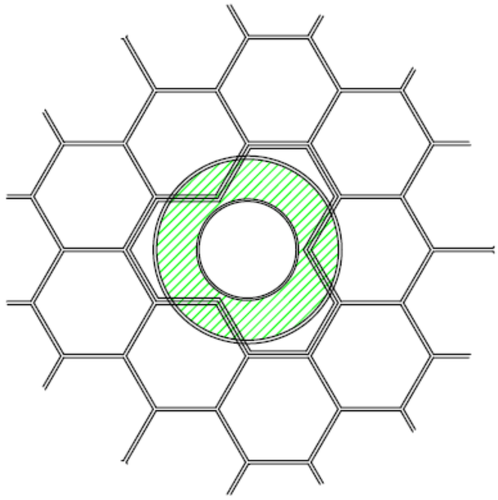

Fig. 6-b: Going from a 3-feeder configuration towards an axi-symmetric design for optimisation of target formation process.

Several iterations where needed to come to the current design version number v0.10LBE. The main revision number is still zero to indicate that some improvements might still be required based on experimental verification. This layout has been chosen to be the reference design for numerical and experimental investigations. The detailed study of the 3-feeder option (figure 6-b) for the LBE downcomer, which has the advantage that optimal use is made of the available space in the ADS core, is not in the scope of the project.

Heat deposition

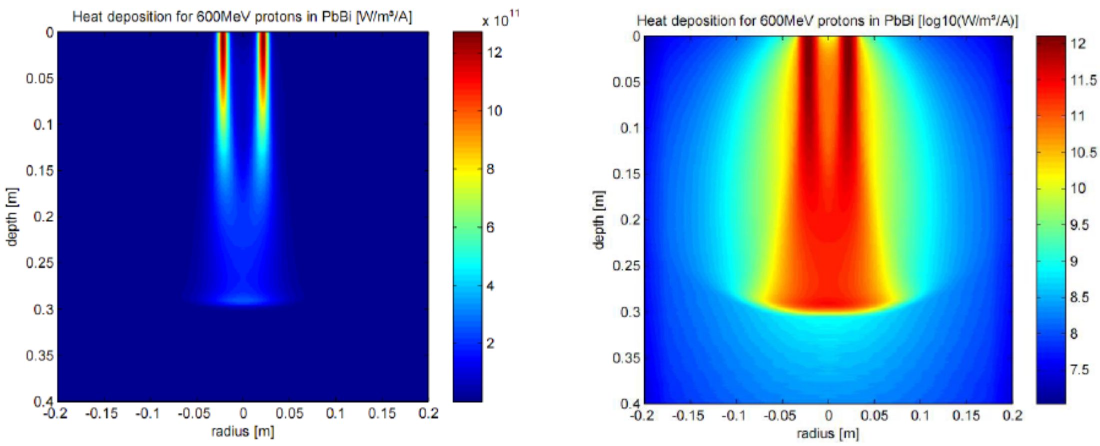

Fig. 7: Linear (left) and logarithmic (right) heat deposition profile of a 600MeV Gaussian beam with σ = 4mm that is swept around a circle with 22mm radius.

The proton beam will be swept around the central recirculation zone of the target, in order to avoid overheating and thus evaporation of this central recirculation zone. Given a certain beam shape and sweep profile Monte Carlo codes like MCNPX can calculate the heat deposition inside the target.

The heat deposition profile of a 600MeV proton pencil beam, Gaussian beam (σ = 4 mm) and swept Gaussian beam (circular sweep with 22 mm radius, σ = 4 mm) have been calculated [6] using MCNPX. The results are shown in figure 7. This last configuration is compatible with the latest design of the XT-ADS target nozzle.

The linear heat deposition profile indicates that most of the heat is generated at the top of the target zone, see figure 8. At 27 cm there is a sudden rise in the linear heat deposition corresponding to the Bragg peak expected from theory. Integrating the linear heat deposition profile results in the total heat deposition in the target: $4.16\ 10^{8}$ W/A. As such, 69% of the total beam power is converted into heat inside the target. For 3.0 mA beam intensity, the heat deposited corresponds to roughly 1.25 MW.

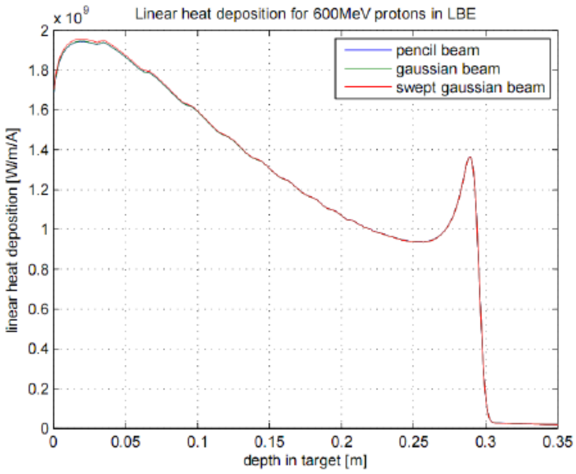

Fig. 8: Linear heat deposition profile for a 600MeV proton beam.

Nuclear and neutronic assessment of the target has also been done using MCNPX. The studies mainly focussed on proton and neutron flux, spallation vector, evaluation of dpa in structure material [7].

Thermal-hydraulics

The current hydraulic design of the spallation target area is the result of a lengthy design process accompanied by a set of full scale experiments. An experimental campaign has started for the improvement and validation of the developed numerical models. Measurement techniques are also developed for thermal-hydraulics experiments and for operational techniques in the XT-ADS. The focus is on local fluid velocity measurement, integral contact less flow meters, and free surface level sensors.

For the spallation target, particular attention has been put on characterization of the free surface flow, flow detachment, study of the 3-feeder option and development of measurement techniques for HLM flows [8].

Since no experiment can demonstrate the ability to transport the deposited heat in a windowless spallation target adequately, validated numerical methods are required. For this purpose, computational fluid dynamics (CFD) simulation methods are the most appropriate. This requires sufficiently accurate free surface modelling, predicting a unique (sharp) interface between LBE and beam vacuum in combination with adequate turbulence modelling. In the European 5th framework project ASCHLIM [9], it was demonstrated that sufficiently accurate CFD modelling of such free surface targets was not possible with the state-of-the-art methods available at that time. Within the EUROTRANS project, the development of CFD methods for the simulation of the removal of deposited heat in the LBE windowless target has progressed substantially [10].

A series of computations have led to a fundamental understanding of the free target flow and the proposed design. Comparison of numerical simulations with a water experiment [11] is shown in figure 9.

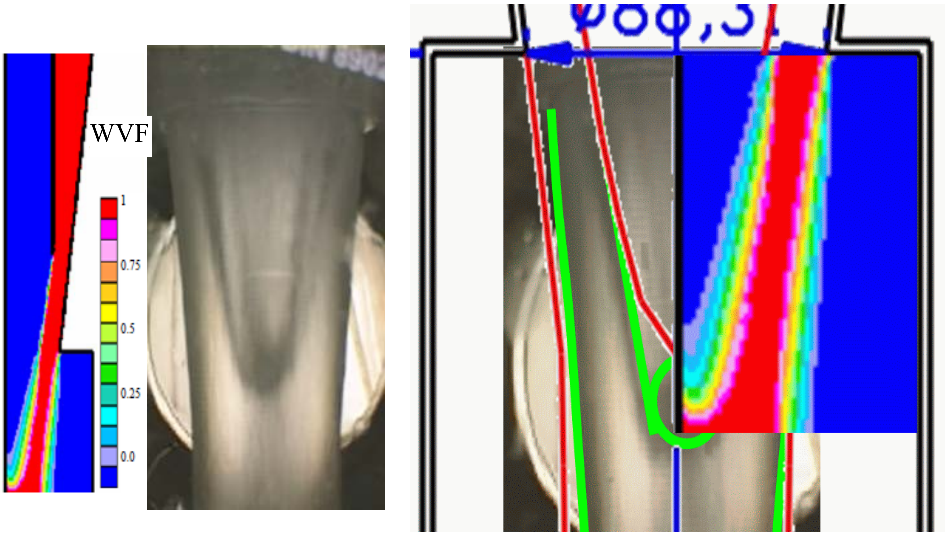

Fig. 9: (left) Predicted water volume fraction (WVF) (red is water, blue is vapor), (center) observed free surface in the water loop experiments. (right) comparison of numerical and experimental results, the red lines indicates the expected LBE flow profile, green lines highlights the experimentally observed free surface [11].

The cavitation model of the commercial code STAR-CD in conjunction with a high resolution interface capturing technique has been employed to compute the flow in the XT-ADS windowless target and related experiments. The numerical scheme is capable to compute the free surface flow in the target and the experiments and can be used in design optimization and parametric studies. A HLM experiment demonstrating the feasibility of stable flow in the HLM windowless target is currently installed in KALLA [12].

Beam target interaction

The purpose of the study performed by NRG is to determine whether the heating from the proton beam results in an expansion wave/pressure wave through the system resulting in LBE splashing after impact of the beam. Splashing could be an issue and is studied numerically. Although results are promising, no firm conclusions can be made at this stage.

Safety analysis

A detailed analysis of the spallation loop behavior during operational and accidental transients using a system code is mandatory. It allows to assess in detail whether the current loop layout can accommodate these transients or whether design measures need to be taken to improve the loop response. The simulations (start-up transient, main pump failure, loss of heat sink …) were performed within the VELLA I^3 Project of the European Commission's 6th Framework Program using a version of the RELAP5/Mod.3.3 code purposely modified to account for LBE properties and behavior. The conclusions of the study could be found in [13]. At this stage, even if the correctness of the approach for the exact simulation of the free surface levels still needs further investigation and confirmation, no showstopper were found.

Conclusions

This paper gives the reference design boundary conditions and the general layout of the XT-ADS spallation target loop. The different design support studies that have been performed within the framework of the IP EUROTRANS DM1 Design are summarized. In this design support studies, no showstopper was identified. These include the spallation target zone and spallation loop thermal-hydraulics, system dynamics, beam impact studies, neutronic and safety analyses. The proof of feasibility of a liquid lead-bismuth eutectic and windowless spallation target for the XT-ADS is made, even if complementary studies and experiments will be necessary before the manufacturing of such a target.

Acknowledgements

The DM1 DESIGN work has been performed under the Integrated Project EUROTRANS (Ref. FI6W-CT-2004-516520) co-funded by the European Union in its 6th Framework Programme. Acknowledgement is also due to all the colleagues of the participant institutes for their contributions in many different topics.

References

[1] H. Aït Abderrahim, P. D'hondt & D. De Bruyn, 2007, "MYRRHA, a new fast spectrum facility", Seminar on Fission – Corsendonck Priorij, 18 – 21 September 2007, Proceedings April 2008, World Scientific, ISBN 978-981-279-105-4, pp. 207 – 221.

[2] M. Dierckx, 2009, "Target area design options for the XT-ADS spallation loop", SCK•CEN report R4649.

[3] M. Reale, 2009, "Description and functional sizing of main components of the reference design of XT-ADS", EUROTRANS deliverable D.1.27 – D.1.28.

[4] M. Dierckx, 2009, "XT-ADS spallation loop operation and pumping options, SCK•CEN report R4666"

[5] R. Stieglitz, 2009, "MHD-Pump for the XT-ADS design", KIT

[6] M. Dierckx, 2008, "Heat deposition profile in the XT-ADS target", SCK•CEN report R4567

[7] G. Van den Eynde, 2009, "XT-ADS Core Summary Report", EUROTRANS deliverable D.1.56

[8] Roelofs F., de Jager B., Class A. et al., 2008, "European research on HLM thermal-hydraulics for ADS applications", Journal of Nuclear Materials 376, 401-404

[9] Arien et al., 2004, "Assessment of Computational Fluid Dynamic Codes for Heavy Liquid Metals-ASCHLIM", EC Contract FIKW-CT-2001-80121-Final Rep.

[10] Batta A., Class A.G., Jeanmart H., 2010, "Comparative Experimental and Numerical Analysis of the Hydraulic Behaviour of Free-Surface Flow in the Water Experiment of the XT-ADS Windowless Spallation Target", Proceedings of ICAPP'10, paper-Id 10342 San Diego, CA,USA, accepted

[11] Batta A., Class A., Dierckx M., Schuurmans P., Van Tichelen K., Jeanmart H., Roelofs F. , 2009, "Hydraulic Design of the Windowless XT-ADS Spallation Target" HeLiMeRT in Europe: SCK•CEN, Mol, Belgium on April 20-22, 2009

[12] A.G. Class, A. Batta, 2010, "XT-ADS Windowless Target: High Resolution Interface Capturing Simulations", Proceedings of TCADS, 15-17 March 2010, Karlsruhe, Germany

[13] N. Forgione et al., 2009, "MYRRHA spallation target loop: RELAP 5 simulation", VELLA Deliverable, European Commission