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A flexible testing facility for high-power targets (Tiara FP7 program)

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A FLEXIBLE TESTING FACILITY FOR HIGH-POWER TARGETS T-MIF

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Abstract

Building on recent experience in the field of applied physics, TIARA Work package n° 9 focuses on target applications for accelerators in Europe. A roadmap for target development has been derived from major achievements in the EU-FP6 and EU-FP7 programs such as the MEGAPIE and EURISOL experiments. The TIARA management board concluded that a worthwhile continuation of such projects would be in the development of a flexible material irradiation facility easily transportable and which could be installed in different laboratories. The power is limited to 100 kW in a very compact arrangement so as to obtain the best neutron economy from a moderate beam power which is more likely to be found in laboratories across Europe. The challenges posed by such a compact design and accompanying calculations are presented in the current work.

Introduction

A dedicated material test irradiation facility is being proposed, derived from prior work funded by the EU FP7 program, the EURISOL Design study, which studied the feasibility of an advanced isotope production facility. The neutron source in EURISOL, was the subject of intense design work and was subsequently tested at full power in a hydraulic test, an experience which can be drawn upon for the current work since the design allowed the passage of a dense proton beam able to generate high neutron fluxes and hence high displacement per atom damages in material or dpas.

As currently envisaged in [1], the testing station will allow critical issues concerning materials under irradiation to be addressed, such as the impact of proton beam irradiation, neutron irradiation, liquid metal corrosion and temperature. The material samples to be investigated in such a facility will be subjected to tensile stress, either constant or cyclical. The facility may also be used for sensor development under irradiation and isotope production, albeit centered on medical applications instead of the exotic nuclei aimed for in the EURISOL design study.

Another aspect of the facility is to aim for greater compatibility with visiting laboratories. The recent spate of projects comprising neutron sources is promising; they have however been one-off designs tailored to a specific accelerator infrastructure. The goal of the current work is to propose a facility that is sufficiently versatile that it may be transported and used in different laboratories

Specifications

Focus on testing materials and sensors under irradiated conditions led to the selection of a key set of parameters defining the most promising design. A survey of compatible installations and in light of past experience, the parameters of the circuits and beam were chosen as follows:

Particles	Protons
Kinetic Energy	200MeV - 1 GeV
Beam shape	Elliptical cross-section $\sigma_x / \sigma_y = 1 / 3\text{-}6$ Parabolic density distribution
Current	< 500 μA
Power	< 100 kW in beam (70 kW thermal)
Primary circuit and Spallation source	Lead or LBE < 15 liter inventory
Secondary circuit	Gallium < 50 liter inventory
Cold Source – open inventory	Air or Water
Saturation radioactivity in primary	~ 20 - 30 TBq / kg
Decay Heat in primary	~ 1 - 2 W / kg
Neutron Flux density	~ 10^{13} n / cm^2 s

Tab.1: Parameters defining the T-MIF facility [1]

The beam deposition profile is elliptical in cross-section as can be seen in the table here-above. With such a profile it is possible to impact a fair length of a tensile stress specimen edge-on and thus obtain high dpas homogeneously distributed on the sample without needing to oscillate the beam to “paint” the specimen with particles. The latter method was attempted in the LISOR program and led to a containment failure leaking radioactive liquid metal to the outside.

Essential features of the new proposed design

The general aspect of the proposed irradiation facility is a cube, 2 metres deep and comprising within it all the necessary systems (figure 1). The interface to the laboratory is limited to the coolant connections to the secondary circuit, the electric energy supply and the signals from the instrumentation.

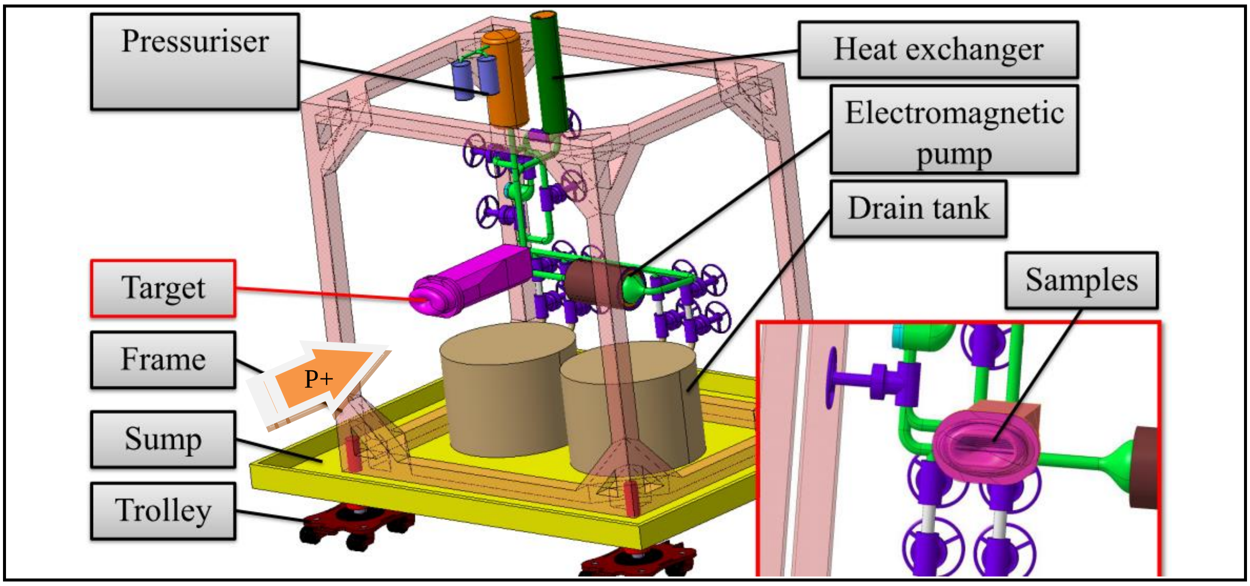

Fig. 1: Overall view of the proposed T-MIF facility
Note that the figure reflects current design status and is not complete

The liquid metal target situated in the center of the facility contains the samples which are subjected to a proton beam (arrow marked P+) creating irradiation damage directly through protons or indirectly through neutrons created by spallation of the surrounding liquid metal by the incoming protons.

Flow control

The liquid metal in the target is re-circulated by an electromagnetic pump (EMP) with an annular design in which a pulsating electromagnetic field created by coils drives the liquid metal with an efficiency of 5-7%. The low efficiency of the chosen pump design is compensated for by the absence of any moving parts, an important consideration in the primary circuit. Unlike most EMP designs, the stator is located inside the annulus inner diameter and the coils are located on the outer diameter. Thus there is no penetration of the EMP coil wires through the liquid metal and all the active parts of the pump are easily accessible. The stator consists in stacks of ferritic steel plates and therefore has no wired connections.

The pump is used to drive the liquid metal through a heat exchanger located at the top of the facility, the position of which was chosen to encourage natural circulation. Since there is a 1 meter difference between the heat source (target) and the cold source (heat exchanger) and a temperature difference of 300°C, a positive pressure difference entraining the flow from the target to the heat exchanger exits;

$$\Delta P = g \cdot \rho \cdot \beta_{Vol} \cdot \Delta T \cdot L = 9.81 \cdot 10'550 \cdot 0.00012 \cdot 300 \cdot 1 = 3'725\, \left[Pa\right]$$

The pressure difference is relatively small, but strong enough to lengthen the coast-down time of the liquid metal over the beam entrance window on the target in the event of a beam trip. This aspect has an important positive safety implication.

Pressure control

The pressure inside the target may be varied as it will influence the dissolution of oxygen in the target. It can also vary over short time periods if the beam intensity varies. It is therefore necessary to provide the loop with a simple means of controlling internal pressure.

The pressuriser situated at the top of the installation (figure 2) is controlled by the release of nitrogen gas into the top of it which is half filled with liquid metal. All gaseous spallation products thus accumulate at the top and lead to a gradual rise in pressure. Release of excess pressure is either gradual through controlled release of these radioactive gases to a series of decay gas bottles or sudden in accident cases, through a series of pressure relief valves and burst disks. The pressuriser will also be provided with gaseous analytical instrumentation capable of measuring activity and gas composition such as a gas chromatograph.

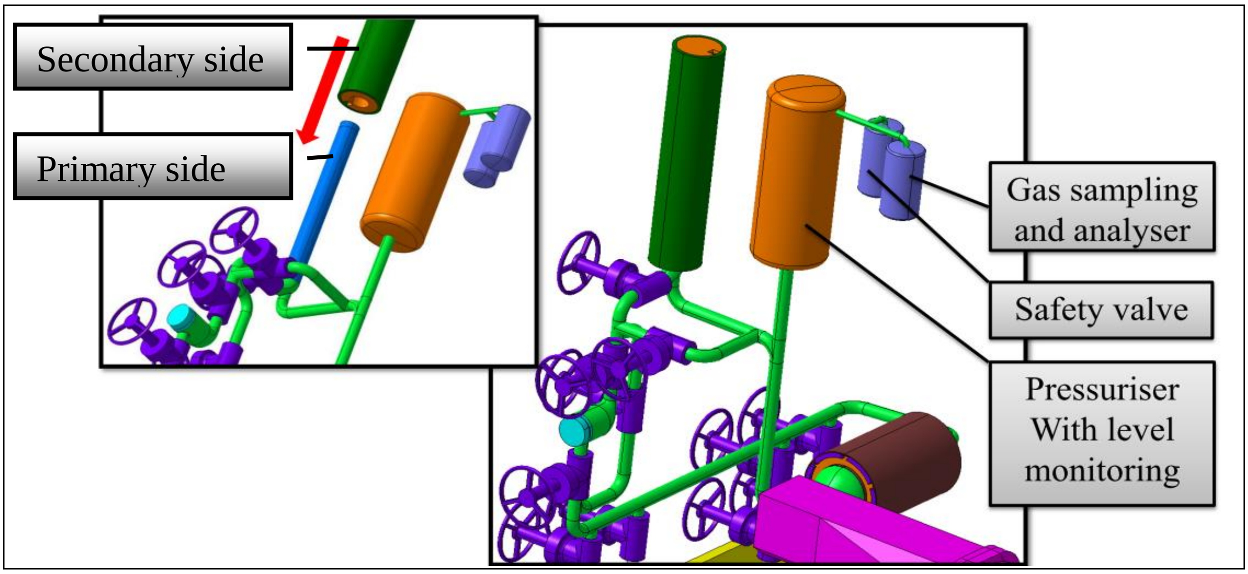

Fig. 2: Detail of pressuriser

An original characteristic of the heat exchanger is the fact it is made up of two separate parts which allow the primary and secondary circuit to separate cleanly (see following paragraphs). This will enhance maintainability and resistance to accidental leaks in the primary circuit.

Target station

The target station at the heart of the facility allows the testing of either material samples or instrumentation under conditions representative of high-power neutron spallation targets. The design (figure 3) of the target is based upon the EURISOL target. The same beam window design is used albeit stretched horizontally to adopt an elliptical section which is compatible with the shape of the beam used to irradiate the samples (as shown in figure 5).

The sample holder located on the guide tube (in grey below) has an inner surface which contains receptacles for loading mechanisms for testing samples (detail in Figure 5). Note that the sample holder can be exchanged for another design. It is simply bolted in place by a series of captured bolts that can be unscrewed by a robot allowing rapid exchange.

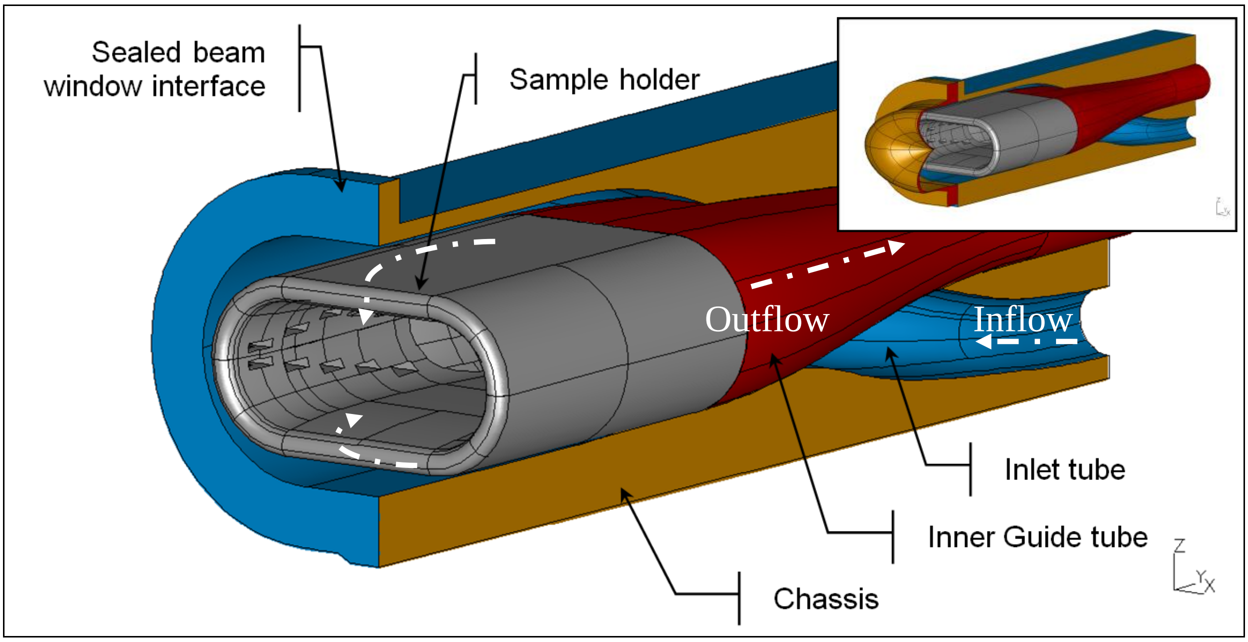

Fig. 3: Detail of target [1]

From a hydraulic point of view, the advantages of this configuration lie in the low pressure loss at high flow rates as was demonstrated in the hydraulic test of the EURISOL target [4]. This improves the economics of the project by allowing the selection of a smaller pump with lower specifications and decreasing the sizing of all the connecting piping.

As illustrated below in Figure 4, the inflow is divided equally over the guide tube and wets the conical surface of the window at a speed of about 1 m/s. The flow rate in this calculation is only half the full speed at full power. With 2 m/s over the window, there is sufficient cooling to evacuate the projected 100 kW of the given past calculations on the EURISOL converter target.

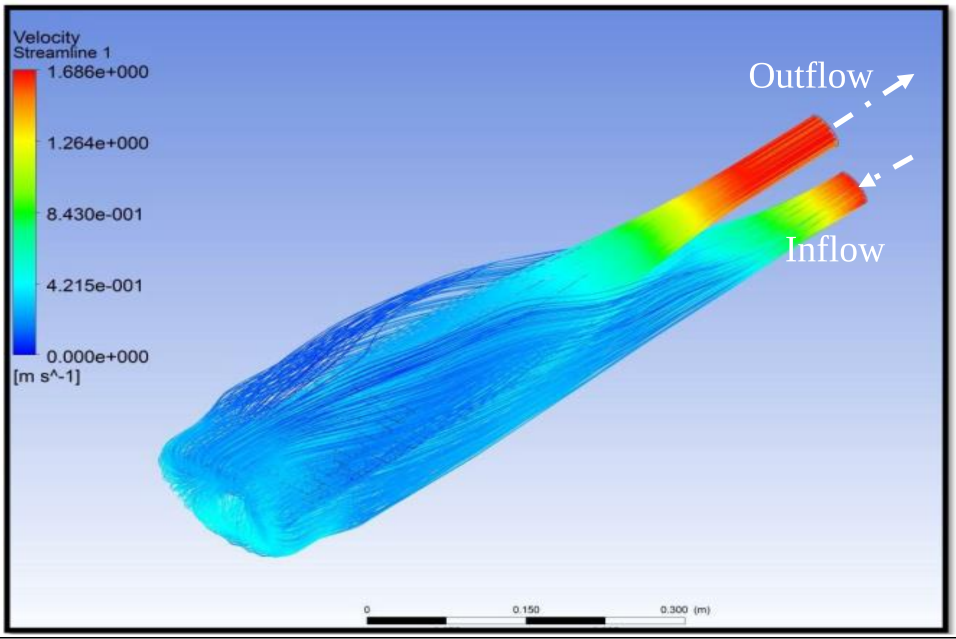

Fig. 4: Flow inside the target [2]

Sample testing

The samples are held in place by a series of rocker arms which transform the compression load form pusher roads into a tension load by inversion around a pivot. The pusher roads transfer a compressive load coming from external electric drive actuators. A compressive load is seen as intrinsically more robust in this design as it allows the sample holder connection to be simplified. Thus the pusher rods interface are in compression and need no connection clips.

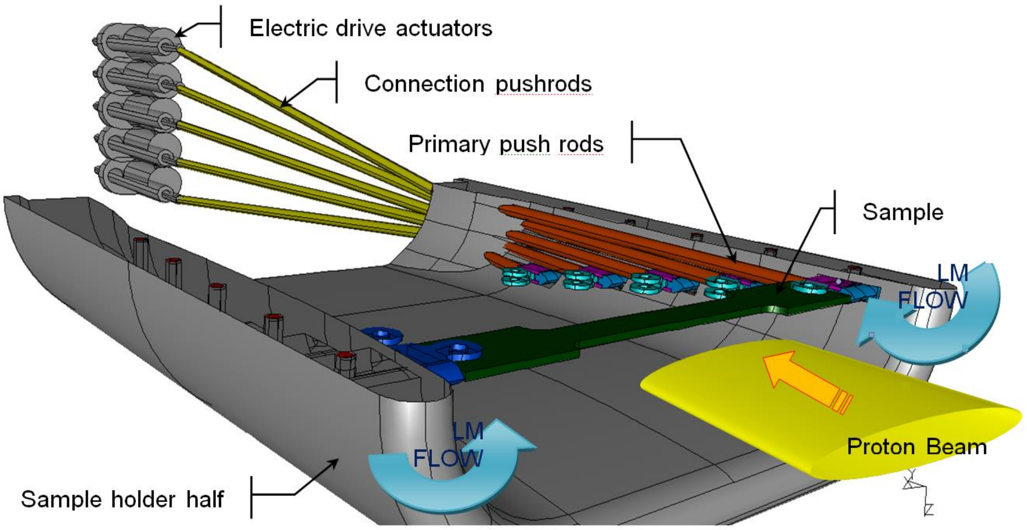

Fig. 5: Sample loading inside the target [1]

The sample holder is essentially a flattened tube split in the middle and which opens like a clam-shell, allowing access to the sample loading mechanism and the samples. As may be seen in the figure, the flattened elliptical beam, which is 1 cm across, fully envelops the sample thickness of 1 mm which ensures a homogeneous distribution of dpa in the sample. Thus the effect of proton damage on a loaded sample under the simultaneous action of liquid metal and temperature may be investigated. The load can be cyclical or constant.

Heat exchanger

The design is based on the concept of a central pin which sends a flow of primary fluid down a very narrow annulus. The secondary fluid surrounds the annulus with a spiral flow. The two fluids are contained in their own vessel and do not share a common wall. On the contrary each part is separated by a gas gap which provides robustness against leaks and a method of detecting leaks.

As explained in the introduction, the heat exchanger allows primary and secondary side to be detached (lower left in figure 6) along with all the assorted cabling and connection for data acquisition or the power supply to the electric drive actuators needed on the target.

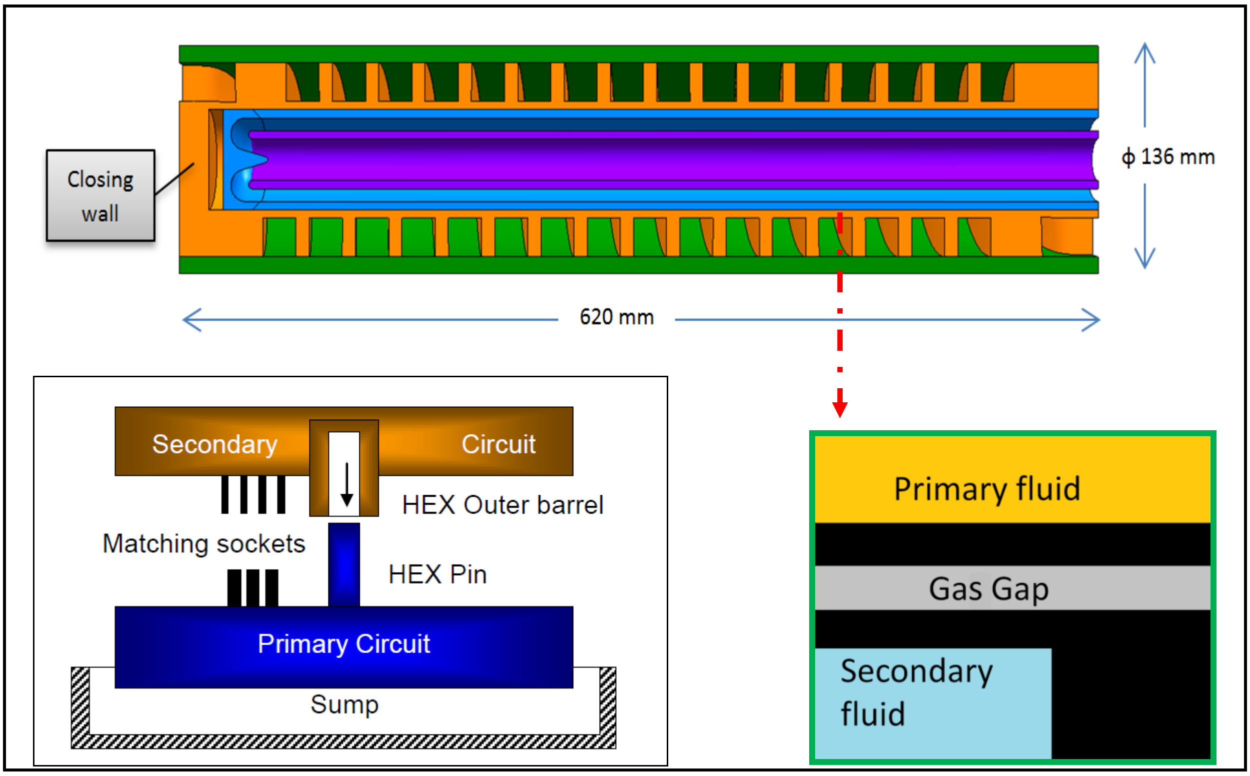

Fig. 6: Principle of the heat exchanger [1] / [2]

The heat transferred in the heat exchanger is estimated according to the latest CFD calculation shown below in figure 7 to reach 130 kW, above the specifications already set out for the design (ref. Tab. 2 below). The additional margin gives some scope for optimizing the gas gap and the nature of the gas contained therein which have not yet been determined.

Power Exchanged	>100 kW
Primary side fluid	Lead or LBE or Mercury 550°C / 250 °C
Secondary side fluid	Gallium 100°C / 75°C
Specific requirements	Leak-resistant Leak detection Able to disconnect primary/secondary Gravity-fed in case of pump trip Minimal inventory primary-side
Pressure	12 Bar

Tab.2: Heat exchanger characteristics

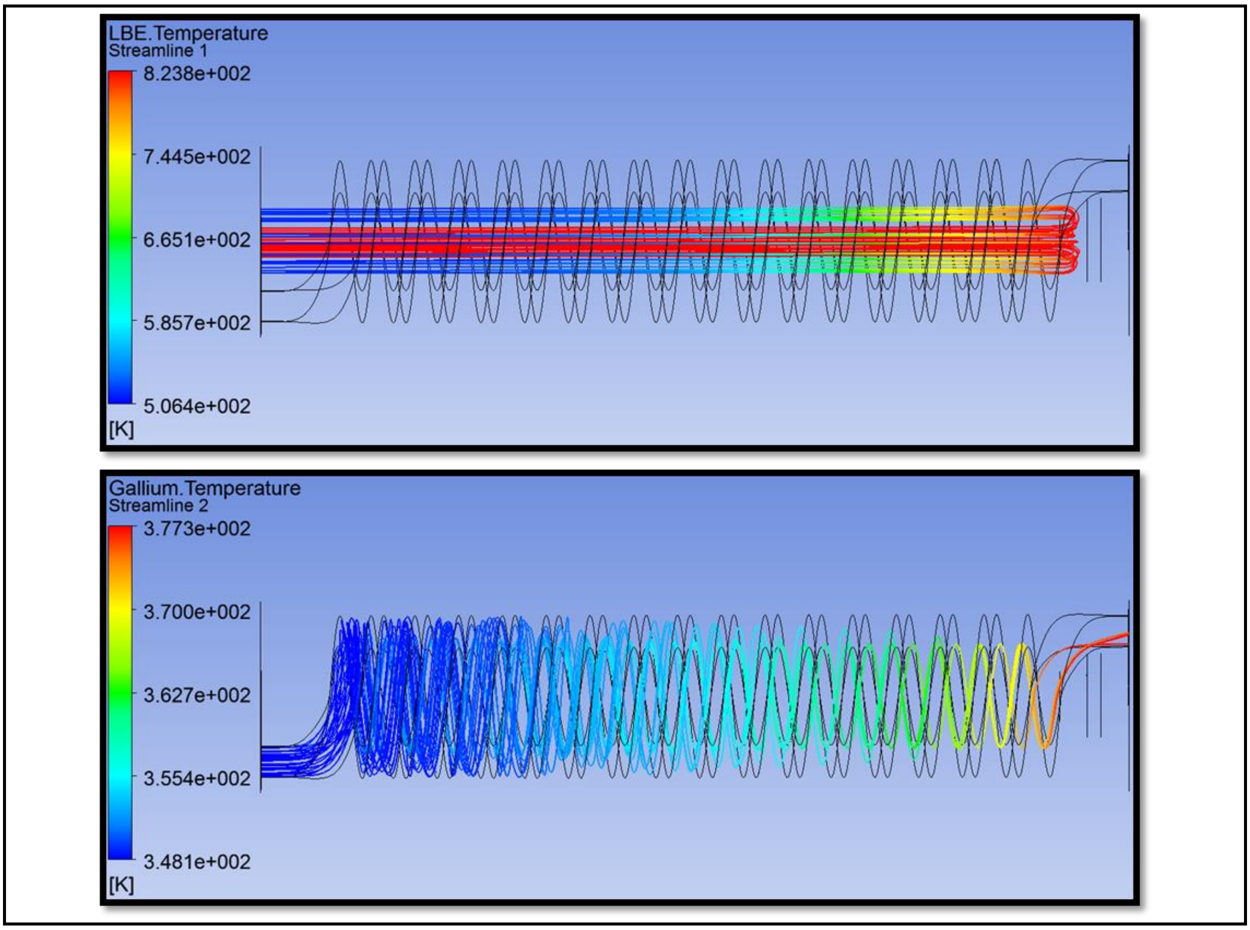

Fig. 3: Flow on primary side (top) and secondary side (bottom) of heat exchanger [2]

Conclusion

An irradiation target is being proposed which should allow significant progress to be made in the field of materials and sensors used in highly irradiated environments. Given the current focus on ever-higher power for scientific instruments, the interest in new forms of nuclear energy, both for fission and fusion, there is a need to continue investigating designs such as T-MIF to allow its full potential to be clearly ascertained.

The team designing T-MIF has recently been strengthened which will focus on specific tasks needed to complete the design aspects, which is now already quite mature. These aspects relate to the neutronic performance in particular, as an estimate of the dpas caused by protons and neutrons for different positions of the samples is required in order to assess the performance of the proposed concept.

A final report which is the EU deliverable is due at the end of 2013 and will recapitulate the design aspects and include further analysis in the field of neutronics and thermal-hydraulics.

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