TIARA-CONF-WP9-2014-002

Test Infrastructure and Accelerator Research Area

Conference Contribution

A spallation-based irradiation test facility for fusion and future fission materials

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25 April 2014

The research leading to these results has received funding from the European Commission under the FP7-INFRASTRUCTURES-2010-1/INFRA-2010-2.2.11 project TIARA (CNI-PP). Grant agreement no 261905.

This work is part of TIARA Work Package **9: TIHPAC R&D Infrastructure**.

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Conference paper submitted to ENC2014

Event website: www.enc2014.org

A SPALLATION-BASED IRRADIATION TEST FACILITY FOR FUSION AND FUTURE FISSION MATERIALS

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ABSTRACT

The EU's FP7 TIARA program for developing accelerator-based facilities has recently demonstrated the unique capabilities of a compact and powerful spallation source for irradiating advanced nuclear materials. The spectrum and intensity of the neutron flux produced in the proposed facility fulfils the requirements of the proposed DEMO fusion reactor, ADS reactors and also Gen III / IV reactors. Test conditions can be modulated, covering temperature from 400 to 550°C, liquid metal corrosion, cyclical or static stress up to 500 MPa and neutron/proton irradiation damage of up to 25 DPA per annum over a volume occupying one litre. The entire "TMIF" facility fits inside a cube 2 metres on a side, and is dimensioned for an accelerator beam power of 100 kW, thus reducing costs and offering great versatility and flexibility.

1. Introduction

The current paper proposes a concept shown in the figure below, which has been evaluated in terms of its ability to irradiate materials at high doses, temperatures and stress.

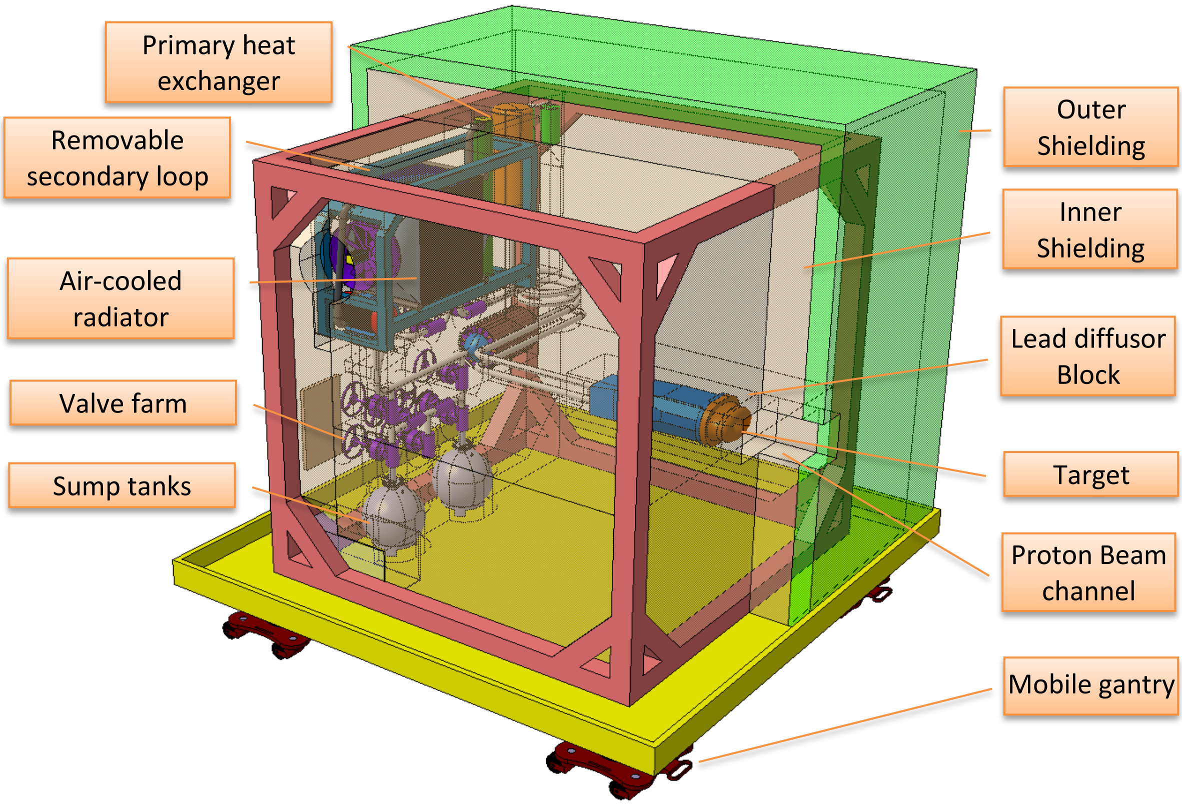

Fig 1: Proposed "TMIF" compact irradiation facility for a 100 kW proton beam line

The development of a Test Material Irradiation Facility – acronym TMIF – was led by the CERN, supported by an FP7 program “TIARA”. Europe maintains a robust technology development program through its research framework program, currently the seventh in the series, or FP7. Institutes are encouraged to collaborate on subjects of joint interest in fundamental or applied research. The TIARA research program, which concluded in 2013, sought to integrate existing European accelerator R&D infrastructure in order to promote state-of-the-art research and strengthen competitiveness and innovation in accelerator science and technologies. Accelerator science is a burgeoning technology, which has much to offer, not only in the medical field and fundamental sciences, but also beyond for energy production.

Aside from supporting directly the operators and users of existing accelerator facilities, TIARA also sought to encourage the establishment of a framework for developing and supporting strong joint European programmes in the fields of:

- Accelerator component R&D
- Education and training in accelerator technology
- Fostering the application of accelerator technology in industry

Europe’s leading research institutes supported the program using their own resources, notably the CEA and CNRS in France, the CERN and PSI in Switzerland, DESY and GSI in Germany , CIEMAT in Spain, INFN in Italy, the UK’s STFC, Uppsala University in Sweden and the University of Krakow in Poland.

2. Accelerator applications

The task entrusted to CERN lies in the development of spallation target technology applications. This area of technology has recently witnessed significant developments in Switzerland, with projects such as MEGAPIE; the first Megawatt-class liquid-metal spallation target developed at PSI [1] and EURISOL; a joint CERN-PSI initiative for a 4 MW-class target [2], [3], [4]. The advent of liquid metal technology has allowed far greater power densities to be deposited by the proton beam in the spallation target, leading to a proportional increase in the local neutron flux. Such local high neutron fluxes open up the field to a vast array of possible accelerator technology applications

Accelerator development itself is the focus of separate work packages in the EU FP7 TIARA initiative and not addressed here. The paper focuses on the neutron source and surrounding equipment which must be further developed for a broader application of accelerator technology. The neutron source is essentially a metal target, which sends out a shower of neutrons when the nuclei of the target material are hit by protons emitted by an accelerator. The neutron source target material may be either solid or liquid, the latter allowing operation at higher temperature and hence under a greater proton beam power density.

2.1 Review of envisaged technical applications

In view of the many years of experience in the development of powerful and compact reliable neutron sources, the following applications can be realistically envisaged today:

- Irradiation facility for nuclear materials,
- Accelerator Driven System (ADS) for the transmutation of radioactive waste,
- Accelerator Driven System (ADS) for energy production,
- Medical isotope production,
- Imaging techniques for fundamental research.

In the development of technology, materials have often been both the initiator, but also the stumbling block for a particular technology to be able to emerge. One need only examine the development of the aerospace industry or the electronics industry, to see how materials are essential to technical progress. The need for improved performance from nuclear materials could very well dictate the pace of development in the other applications listed above. It seems logical therefore, to prioritise a facility for testing materials under high irradiation. Furthermore, allowing for some modifications, the facility could be extended to areas such as sensor development and isotope production for which highly concentrated neutron fluxes could be of use. These applications are however not covered in the current study.

2.2 The specific need for material irradiation facilities

The development of high-energy physics and its many applications is proceeding apace, with a demand for ever greater power densities. Specific projects such as the neutron beam facility ESS in Lund, Sweden focuses on the pure sciences. Others, such as the ADS project MYRRHA in Belgium or the fusion reactor ITER in France are attempting to harness new methods of energy production from the atom. In all cases, increasing power densities are aggravating the damage caused by irradiation to materials.

The standard method for irradiating materials today is through the use of high flux reactors such as the BR2 in Belgium. These reactors are reaching the limit of their design lives and are being challenged by accelerator-based irradiation facilities such as the LISOR or SINQ facility at the PSI [5]. The latter tend to focus on smaller samples due to the reduced volume available, however investigation techniques have improved considerably such that valid material values can be gained from samples well under a cm in length.

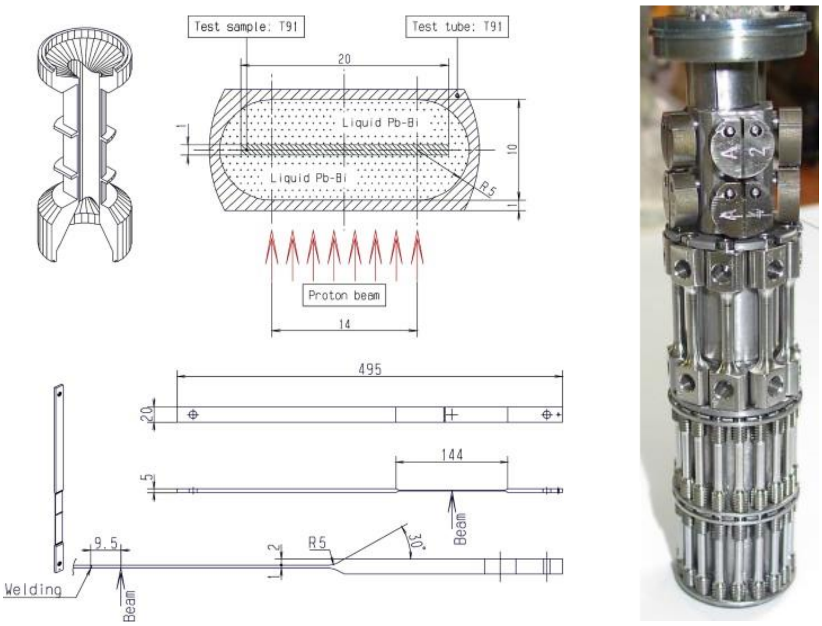

Fig 2: Irradiation samples arrangement in LISOR (left) and BR2 (right)

2.3 Specification of a material irradiation facility

Testing nuclear materials with an irradiation facility should at least include combinations of irradiation and temperature along with stress. Such conditions are the focus of the proposed development.

Required testing conditions have been derived from a review of the likely demands from projected facilities, which are the basis for the development. The parameters needing to be included in the test facility are:

- Neutron irradiation (from spallation of protons on target)
- Proton irradiation (directly from the beam)
- Static/cyclic stress
- Liquid metal Corrosion
- High temperature

These requirements can be met by immersing the samples in the spallation zone of a liquid metal spallation source; this is the solution retained in the present study. A configuration consisting in a liquid metal spallation source (or target) driven by a proton beam and surrounded by a blanket has been optimised to increase DPA production in the samples.

The accelerator, an essential component, is not covered in this study but has been simply specified as realistically as possible. The requirements on the accelerator are kept to a minimum as it can drive a large part of the cost. The parameters given in the table 1 could be met either by compact cyclotrons that have already been developed by some commercial companies or by diverting part of the beam from a large facility as exists in the US, Europe or Japan.

Particles	Protons
Kinetic Energy	200MeV – 600 MeV
Beam shape	Elliptical cross-section σ_x / σ_y = 1 to 6 Gaussian density distribution
Current	< 500 μA
Power	< 100 kW in beam (70 kW thermal)

Tab 1: Characteristics of the beam used in TMIF

In terms of the overall layout of the facility, a cube approximately two metres on a side should contain all the hardware. It must be mobile and transportable so that it can be used in many laboratories around the world. Its radiation characteristics should be compatible with accelerator laboratories and isotope production facilities such as exist already in hospitals.

3. Feasibility study

The scope of the work included a detailed feasibility study of a facility applying accelerator technology, it did not provide for any component testing. The study focused on aspects of performance, reliability and safety, resulting in a detailed engineering study [6] which is the backdrop of the current paper. In order for it to be suitable for industrial use, the study must ensure that the design:

- is sufficiently compact, safe and reliable to operate in major urban centres,
- uses established technological choices that can be licensed,
- is a cost-effective alternative to reactors.

The feasibility study concentrated on aspects most critical to a robust assessment of these goals. Hence the study initially concentrated on the samples, continued on to examine cooling and critical stresses in the target. It then examined heat exchange, the primary circuit and in particular how to isolate the primary from the secondary circuit, a common cause of contamination accidents. And finally global shielding matters were investigated.

Neutronics aspects were calculated using FLUKA in order to ensure sufficient irradiation on the sample and in keeping with the ALARA principle for the operator.

3.1 Sample testing environment

The successful use of small samples in LISOR has been replicated also in SINQ and has been retained for the current proposal. In LISOR however, the DPA value is increased by “painting” the sample with the beam which leads to very high and complicated stress patterns due to the highly focused mobile beam spot on the sample [5]. To avoid this problem, TIARA trains the beam to hit the sample side-on so that the entire sample breadth is impacted by the proton beam as illustrated in the figure below. Small samples can then be cut out along the length of the loaded sample as in LISOR, but with the advantage of a homogeneous stress distribution in the sample due to the disposition of the loading mechanism shown in schematic form in figure 3 and in greater detail in figures 5 and 6.

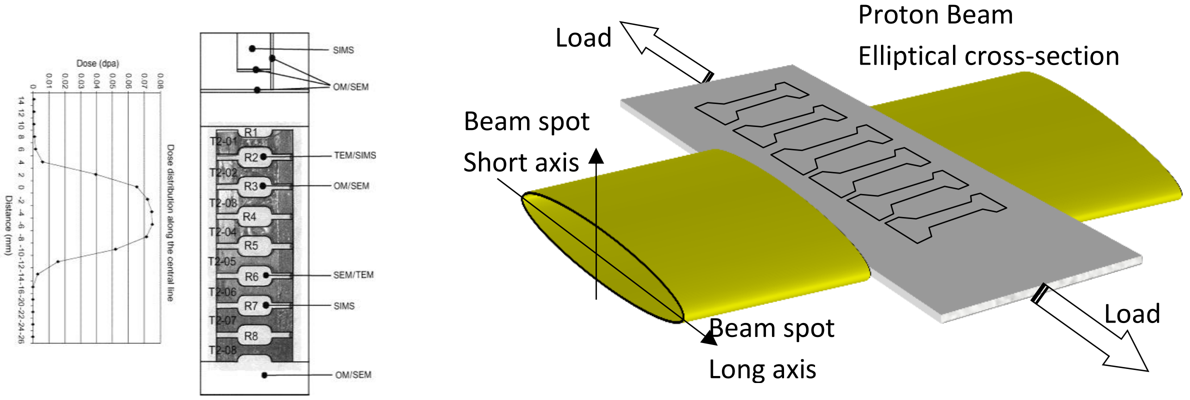

Fig 3: Irradiation samples from LISOR (left) and proposed irradiation in TMIF (right)

Applying the principle outlined above has been a major challenge in the early design phase and has led to much iteration. After studying many options, the general disposition of the EURISOL target has been chosen as the baseline. In this target shown below, the liquid metal enters an annulus from a pipe below the target and reverses back into guide tube at the so-called “beam window”. The “beam window” allows the passage of a proton beam into the liquid metal inside, hence its name; this thin-gauge concave conical end-cap bears the full force of the impact of the beam. It is however extremely well cooled by the liquid metal flowing past the window inner surface and is thus able to withstand the high heat deposition.

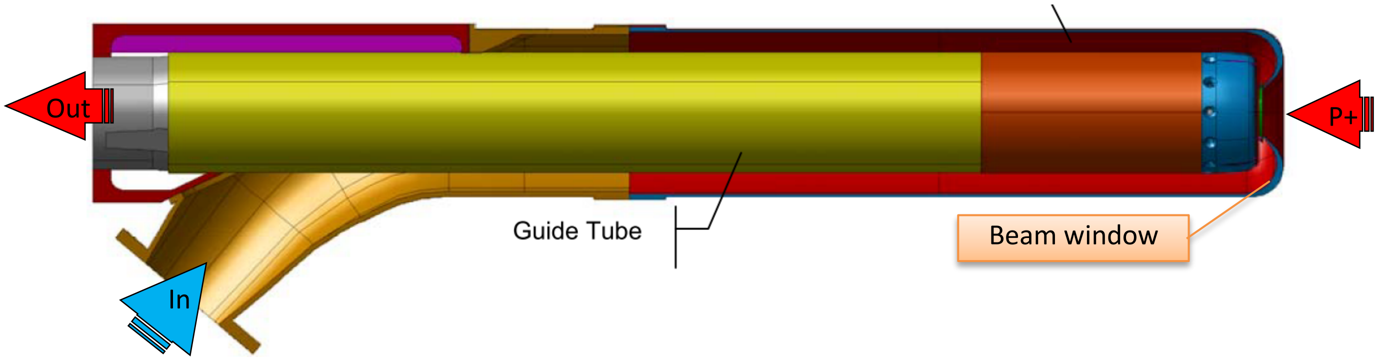

Fig 4: Original Eurisol liquid metal target concept in side-view, basis for current target

The samples are positioned precisely at the entrance to the guide tube, just behind the window in order to maximise the DPA from both protons and neutrons (Figures 5, 6). The beam after passing through the cusp-shaped window impacts directly the samples creating on the one hand DPA directly from proton interaction. Also, the beam impacts the surrounding primary fluid, a heavy nuclei, resulting in the production of a large number of spallation neutrons, which likewise contribute to the DPA irradiation damage in the samples. Thus irradiation, temperature and corrosion are effects represented in the proposed design.

Compared with the original EURISOL design in figure 4, the cylindrical tubular arrangement has been widened in transverse direction to accommodate the samples as shown in figure 5. The detailed engineered solution is shown hereafter. The target contains a disposition of samples across the entrance of the return guide flow, which are thus impacted side-on by the beam and very well cooled by the returning flow of liquid metal. The samples are held in a sample holder which is the forward end of the internal guide tube via which the fluid leaves the target. Actuators acting on rocker arms apply a cyclical or static stress from the outside.

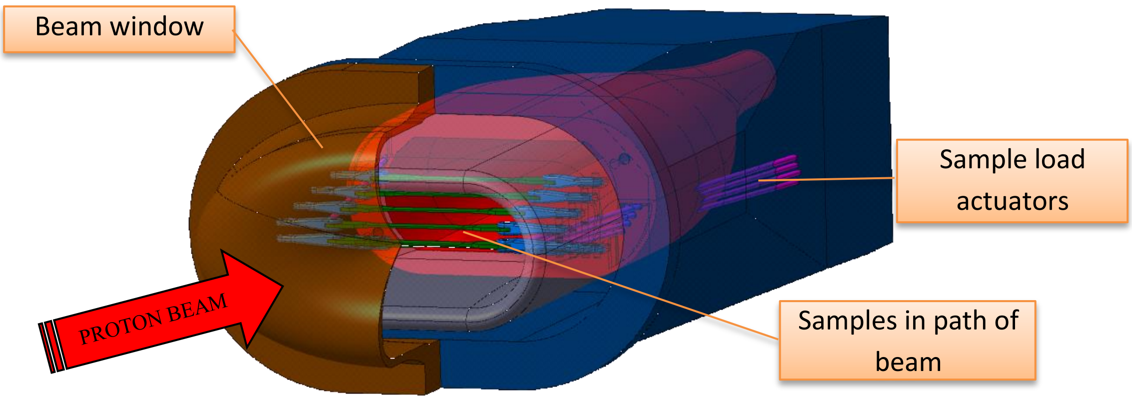

Fig 5. Disposition of samples in proposed irradiation target

The mechanical loading system allows a constant or cyclical stress to be imposed on the samples. This aspect is particularly important to material embrittlement studies or fatigue studies. The method of applying stress to the samples is illustrated in the following figure 6.

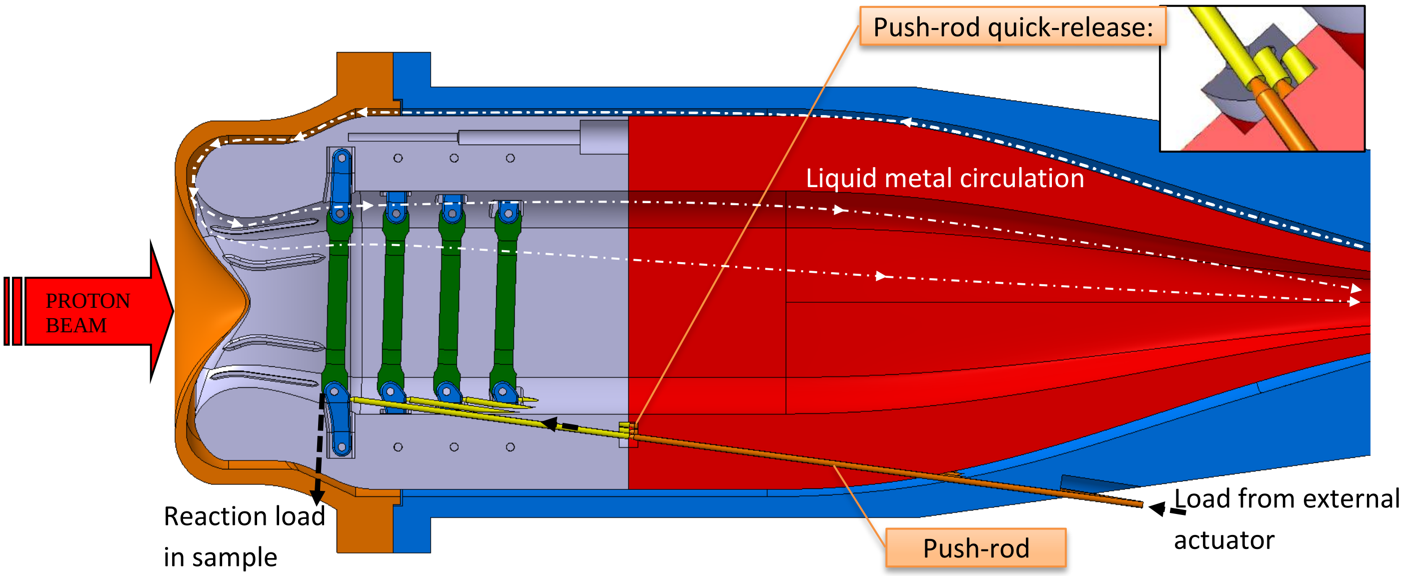

Fig 6. Loading of samples in proposed irradiation target

Figure 6 illustrates how the samples are loaded via push rods driven by actuators situated outside the target. The push rods are able to penetrate through dedicated channels isolated by bellows ensuring leak-tightness of the primary circuit. The pneumatic actuators are themselves located well outside the maximum neutron flux to increase reliability.

The push rods are split into two parts, one part remaining attached to the target, the other located in the sample holder. Since the push rods apply only compression loads, the interface between the two sets of push rods (see inset in figure 6 above) between the dismountable sample holder is easy to disconnect, there are no pinned or bolted joints. The final sets of push rods located in the sample holder apply a compressive force to a rocker arm (in blue in figure 6 above) which de-multiplies the load into a tensile stress applied to the sample. A relatively modest load from the actuator ~ 800 N is sufficient to guarantee 500 MPa is attained in the samples.

3.2 Sample manipulation, maintenance

Sample manipulation is generally difficult in presence of high irradiation doses. It is therefore important that their manipulation be simplified so as to allow the use of robust robotics for the early removal of samples. The use of robotics is preferable to a long cooling-down period as it allows maintenance to be performed quickly and down time to be minimised. First, all the liquid metal must be evacuated from the primary loop to the decay sump tanks located at the bottom of the facility (see figure 1). Then, the window followed by the detachable sample holder can be removed easily using a grappler as shown hereafter in figure 7.

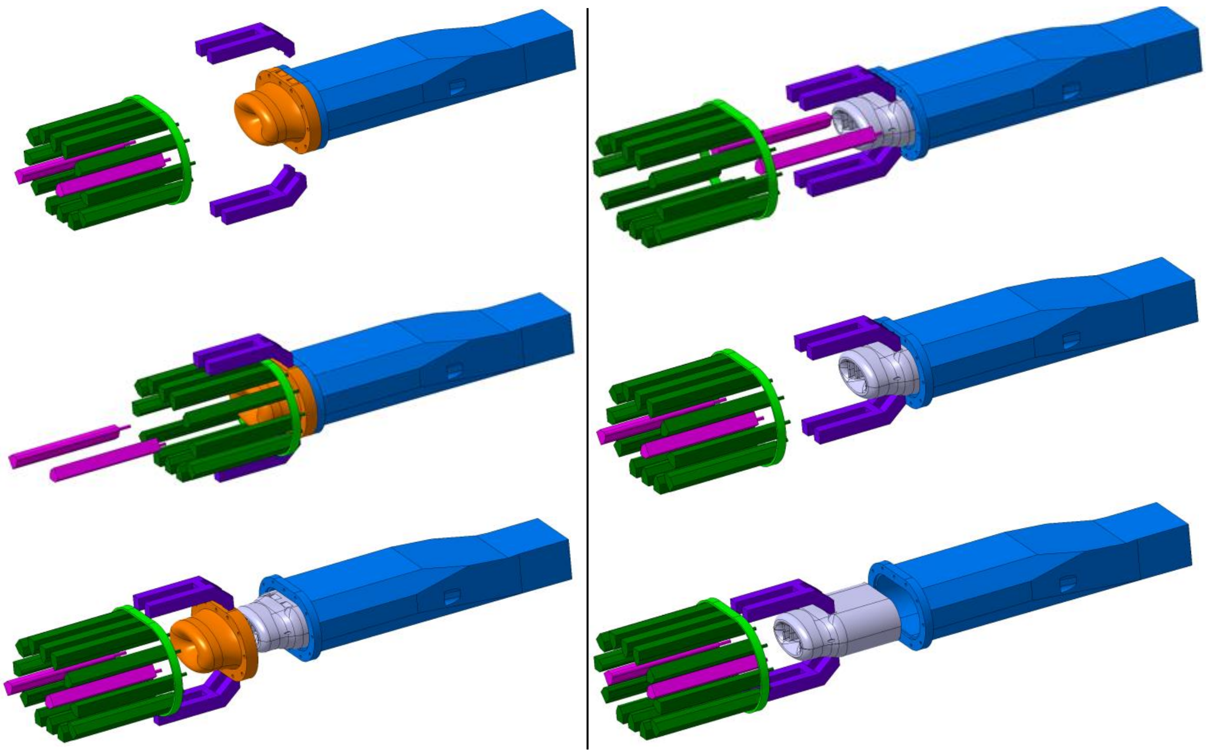

Fig 7. Removal of window (left) and sample holder (right)

The method for removing the window is depicted on the left-hand side in figure 7, consisting in a simple grappler (in purple) latching on to grooves on the window flange (in orange), whereupon electric torque wrenches (in green) advance onto the captured window bolts, thus releasing them. The window can then be removed and falls into a basket after release from the grappler. Once the window has been removed, it is processed as waste and can be replaced after sample exchange. Changing only the window avoids scrapping the entire target; a costly waste treatment expenditure.

Figure 7 on the right-hand side shows the method of removal for the sample holder, which follows a similar path, using the same grappler but a different set of electric torque wrenches (in pink) as the sample holder is held in by another set of only two bolts. The method for unlocking the two halves of the sample holder is explained in the next figure 8. Two lugs either side of the sample holder halves, ensure the two halves remain locked together when the captured bolts are fully screwed down. Once the two bolts are unscrewed, the lugs are freed and the two halves can be released by the grappler into a basket which can then transport them to a shielded cell for removal of the samples.

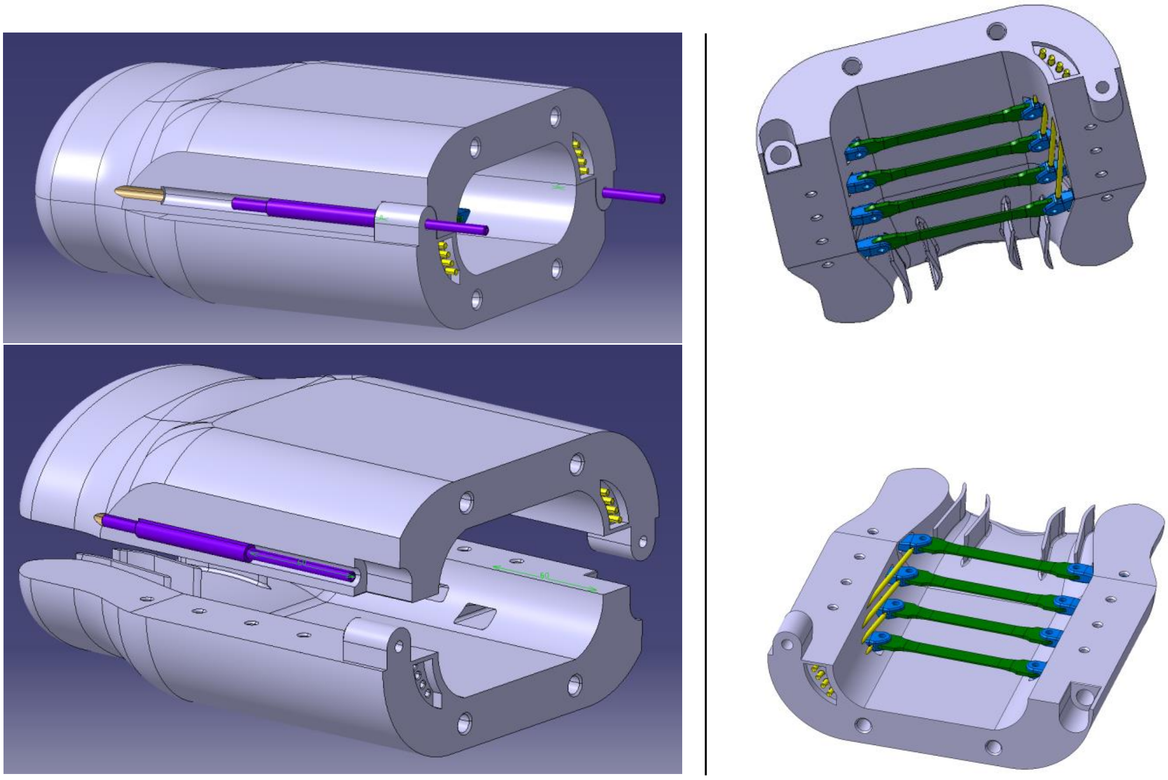

Fig 8. Opening the sample holder (left), disassembled view (right)

All the operations described here-above can then be repeated in the reverse order to mount fresh samples and a new window onto the target. During these manipulations, the fluids in the primary and secondary circuit can be changed, alongside maintenance of pumps, instrumentation etc. This allows a quick turn-around of the facility to increase irradiation time.

3.3 Thermal-hydraulic analysis

The circuits used for absorbing the heat of the beam are summarised in table 2 hereafter. Lead was chosen for the primary circuit as it is the spallation medium as protons react with lead resulting in a good spallation yield. The absence of the formation of Polonium from Lead is an advantage in terms of radioprotection compared to Lead-Bismuth Eutectic despite the latter's lower melting point.

Primary circuit and Spallation source inventory	Lead < 15 litre (150 kg)
Secondary circuit inventory	Gallium < 5 litre (25 kg)
Cold Source – open inventory	Air
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 2: Characteristics of the circuits

The secondary fluid is Gallium which has the advantage of also being a liquid metal and hence unlikely to react chemically with lead, unlike water or oil for instance. The secondary circuit is not bombarded by protons and therefore unlikely to activate.

Finally the heat released to the secondary circuit is evacuated by an air-cooled radiator into the laboratory, which must therefore be able to ventilate a 70 kW heat source to the outside.

Safety aspects are enhanced in the design of the heat exchanger between primary and secondary circuit, which has no common wall (refer to [6]). Hence any leak penetrating from one side would be captured in an interstitial gap between the two exchange surfaces, allowing its detection and mitigation. This design is not essential in terms of the influence on sample operations. Hence only the thermal-hydraulics inside the target itself are reported in the current section and the reader is referred to the report in [6] where this design and other thermal-hydraulic aspects are analysed in depth.

The hydraulic design of the target must be able to function over a wide range of speeds, so as to allow the temperature in the sample to be varied. The simplest method of controlling the sample temperature is therefore to change the flow rate; since the deposited power in the liquid metal and samples remains constant, the temperature will increase with decreasing flow rate and vice-versa. The method should be stable as the heat capacity of the liquid metal is quite high.

The inlet section of the guide tube has proven to be quite a challenge due to its non-symmetric flattened shape. In the final iteration, guide vanes have been added to avoid the formation of recirculation zones in the backwash of the proton beam heat deposition zone. These could accumulate a significant amount of heat as the heat deposition is intense. The iterations have been carried out for a flow rate of 4 kg/s; representing the lower end of the spectrum in terms of speed in the target, for which temperatures and hence overall safety aspects are the most challenging. The maximum flow rate is 38 kg/s.

A final iteration of the design is shown in figure 9 along with the flow patterns both in vertical and horizontal planes. High velocity regions are evident in the beam deposition region, thus ensuring temperature remain low. The high velocities along the cusp beam window are also evident in the figure, as required for beam window cooling and low thermal stresses.

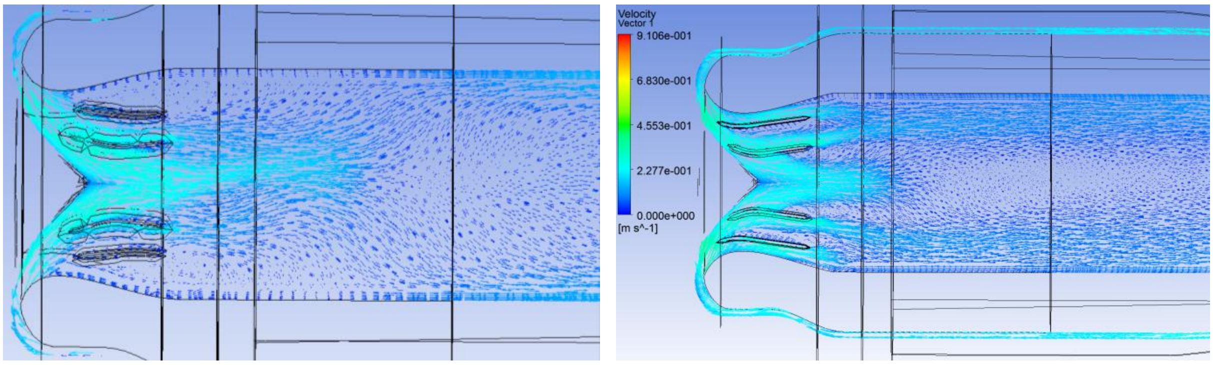

Fig 9. Velocity flow field in horizontal plane (left), vertical plane (right)

3.4 Analysis of the neutronics performance for heightened DPA

Crucial to the overall performance of the facility is the neutronics calculation of doses on the samples as this constitutes the main goal of the facility. A full model detailing the samples and a rough model of the surrounding components such as the shielding has been developed, as described in [6].

The primary aim is to increase the DPA in the sample by optimising the beam. The beam parameters have been varied with respect to energy, current and sigma-width in X and Y directions perpendicular to the beam axis. The design study has assumed an elliptical beam spot with a long axis parallel to the sample length in order to maximise the impact of the proton beam on the sample as shown in figure 10 below.

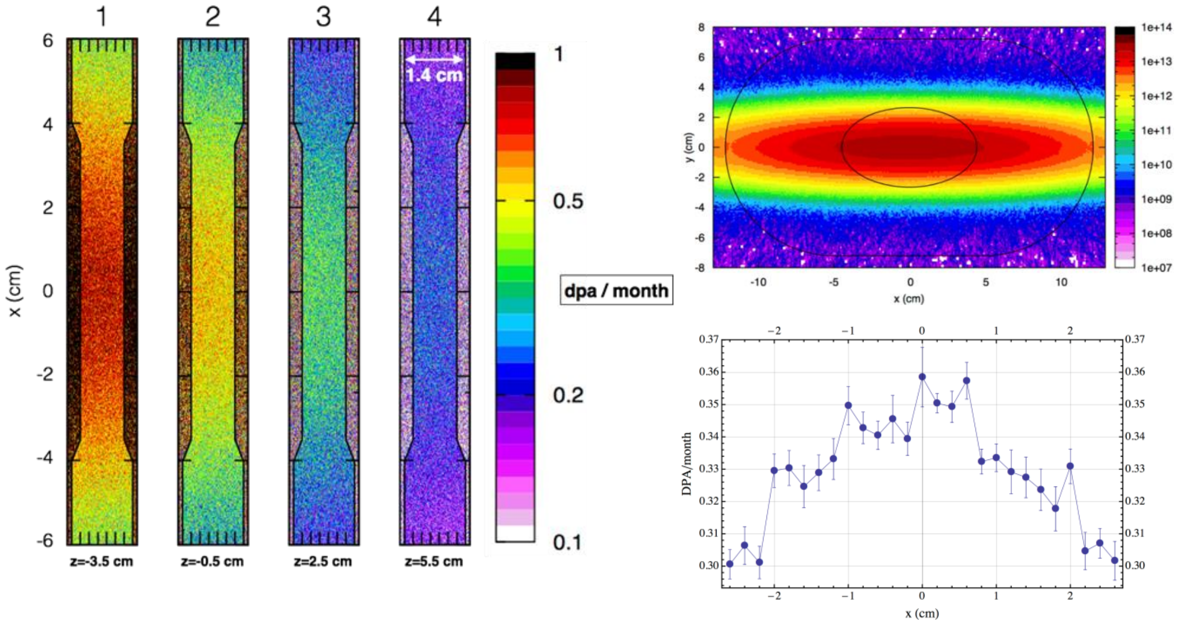

Fig 10. DPA distribution between samples (left) in first sample (bottom right) for a proton beam profile σ_x / σ_y = 6 (top right)

A more circular shape has been found to be more favourable as the proton-DPAs are less diluted over the entire sample. Indeed, a more circular beam spot leads to a maximum of 25.7 DPA per annum in the most irradiated sample, the one closest to the beam window, using a beam energy of 200 MeV, a current of 500 μA and a beam spot of 1.7cm x 1.0cm. The beam energy is optimal for DPA production between 200 to 400 MeV, which is well within the range of many experimental facilities such as SINQ in Switzerland or J-PARC in Japan. The 200 MeV range is within reach for current commercial development of cyclotrons.

	DPA per year (stat. uncertainty < 1%)		
Beam Spot	σ_X : 6 cm σ_Y : 1 cm	σ_X : 1.7 cm σ_Y : 1 cm	
Sample N°	600 MeV 166 μA	400 MeV 250 μA	200 MeV 500 μA
1	8.8	23.0	25.7
2	6.0	13.9	1.7
3	4.1	8.3	1.0
4	2.9	5.0	0.6

Tab 3: Effect on DPA of varying the beam parameters

The table above lists the average yearly DPAs over the sample for different settings of the beam, showing how it affects the relative distribution of DPA amongst the samples. A study of the ration of neutron-to-proton induced DPA (Table 4) indicates that with a wider beam the relative average contribution of protons can be very much reduced, due to a “dilution” or spreading of the beam. On the other hand, in the case of more circular beam, the proton contribution can remain quite high, particularly in the central region which concentrates the high DPAs.

Sample	Beam	DPA/year (stat. uncertainty)	Contribution from protons	Contribution from neutrons
1	σ_X : 6 cm σ_Y : 1 cm 600 MeV	8.76 (0.4%)	44.3%	55.5%
2		6.00 (0.5%)	34.9%	63.8%
3		4.08 (0.5%)	25.9%	73.2%
4		2.88 (0.6%)	20.0%	79.1%
1	σ_X : 1.7 cm σ_Y : 1 cm 400 MeV	22.92 (0.1%)	58.1%	40.6%
2		13.92 (0.3%)	49.8%	49.2%
3		8.40 (0.3%)	44.5%	54.5%
4		4.92 (0.4%)	45.1%	54.0%

Tab 4: Balance of proton-neutron induced DPA with two different beams

Hence it is possible by changing beam parameters to vary quite widely the degree to which DPAs are produced by protons vs. neutrons. The ability to adapt the part of neutron-induced DPA is of worth to fusion research. Studying various ratios is in itself an interesting capability, to judge whether the two types of DPAs have a similar effect on the materials being tested.

A significant achievement of the proposed TMIF design rests in its ability to reproduce the spectrum required for DEMO, the future demonstrator fusion reactor. In figure 11 below, the spectrum of the basic 100 kW version of the proposed TMIF facility and an increased power version at 1 MW have been plotted against the spectra of IFMIF and MTS, a 1 MW facility proposed by LANL. The figure demonstrates how the 100 kW version of TMIF reaches the same values as the 1 MW facility MTS. The 1 MW version of TMIF delivers the same spectrum and neutron flux intensity as the 5 MW IFMIF. Note that in engineering terms the critical items in TMIF such as the target and heat exchanger are quite adaptable to 1 MW, however a 1 MW version has not been calculated in depth in the current design study.

The total volume available for testing at high DPA in T-MIF is approximately 1.2 litres. All the volume cannot be used as channels must be left open between samples for circulating cooling liquid metal; therefore about 0.5 litres can realistically be occupied by samples.

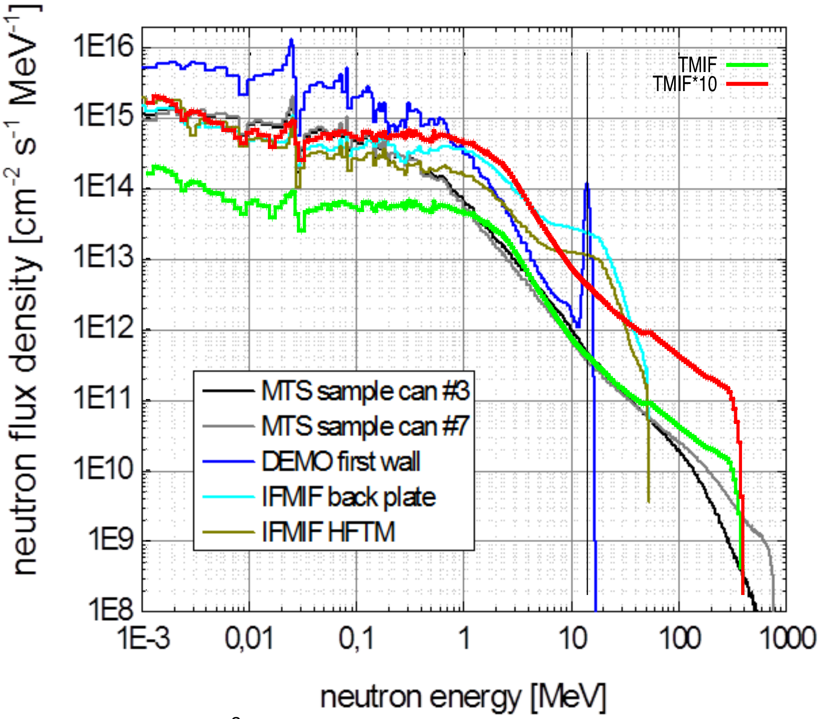

Fig 11. Neutron spectrum (n/cm^2/s/MeV) in TMIF facility compared with MTS, IFMIF, DEMO

A feature of TMIF is its ability to create DPAs from both protons and neutrons, the relative proportion being a function of the position of the sample (see Fig. 10 and Tab.4). Damage on the first wall of DEMO in terms of DPA peaks at 16 [dpa/yr] on the inner surface and declines rapidly further outboard [8]. This figure corresponds well to the DPA production rates calculated above in table 4 for the 100 kW baseline version of TMIF. Beyond the level of DPA however, production rates of specific isotopes through transmutation are of interest. Specifically Helium production rates give cause for concern as this gas tends to cluster in the form of micro-bubbles in structural materials such as steel and cause its embrittlement. A study of He production in TMIF samples is on-going at the time of writing, however estimates are possible based on the literature available such as in [7] and [8].

3.5 Estimate of Helium production rates

Garner *et al.* report in [7] on the production rates of Helium impacted by both neutrons and protons. Gilbert *et al.* in [8] have studied the likely production rates of Helium in various structural materials of DEMO under a representative fast neutron flux. By comparing these two sources with the neutronics analysis for TMIF, it should be possible to gauge the suitability of the proposed TMIF facility for testing material samples under conditions representative of DEMO operational conditions.

Overall, the neutron flux spectrum expected for DEMO is dominated by fast neutrons clustered around a 14 MeV peak. The authors in [8] point out the importance of the hard spectrum in terms of generating Helium clusters because of the very high "*threshold energies for the gas producing reactions; for instance the (n,α) reaction on 56Fe, which is the main production route for He, has a threshold of approximately 3.7 MeV*". Figure 11 above shows that the baseline 100 kW version of TMIF produces a neutron flux (green line) which comes quite close to the spectrum of the DEMO first wall (in blue), particularly in the high energy region of the neutron flux which would be responsible for producing Helium. Moreover, although the overall level of neutron flux in TMIF is slightly less than in the DEMO first wall, the tailing-off of the TMIF spectrum extends towards a far higher energy band. Hence it could be assumed that the helium production rates in the TMIF samples would be close to that expected in the first wall of DEMO. Apart from Helium production in steel, other transmutation products such as Re in W are also a cause for concern to the DEMO project. Since the neutron spectrum in TMIF is similar in terms of overall flux and energy distribution of the neutrons, the proposed facility should be able to replicate the testing conditions required for DEMO.

A more detailed assessment is possible from the test results in [7] which are fairly representative of TMIF; this should enable a rough estimate of Helium production in TMIF to be derived from these *measured* Helium production rates. In [7] an 800 MeV proton beam with a Gaussian profile hits a target edge on, resulting in a mixed proton/neutron field in the centre and a more neutron-dominated filed towards the two outboard ends of the target. Table 1 in [7] lists the helium production rates at different positions in the sample which are submitted to different ratios of neutron and proton DPA. For instance in the case of Inconel 718, the Helium production rate in the centre of the sample on the beam axis is 79 [appm/DPA], whereas 1 cm off axis from the beam centre it decrease to 65 [appm/DPA] and 3cm off-axis from the beam centre it further decrease to 60 [appm/DPA] . With stainless steel 316L the Helium production rates are 70 [appm/DPA] in the centre and 55 [appm/DPA] 3cm off-axis. Hence the measurements appear to demonstrate that DPAs produced by protons result in slightly more helium production than DPAs produced by neutrons. Since Helium embrittlement is a major cause of concern for DEMO, producing DPAs with a higher proportion of protons to neutrons could be beneficial to testing materials conservatively.

The production rates estimated in the DEMO first wall according to the calculations in [8] is 100 [appm/yr] for Helium. If the helium production rates per DPA derived from the measurements in [8] are used to estimate Helium production in TMIF, the following prediction can be made:

- From [8]: 80 [appm/DPA] for proton-rich relative DPA contribution
- From [8]: 50 [appm/DPA] for neutron-rich relative DPA contribution
- From table [4]: 22.9 DPA in proton-dominated specimen
- From table [4]: 2.88 DPA in neutron-dominated specimen

Hence the Helium production rate in the samples could be made to vary from 144 [appm/yr] up to 1832 [appm/yr], the latter value exceeding the highest estimate for Helium production in the first wall of DEMO for three full years of full power; approximately 450 [appm].

3.6 Analysis of the shielding

Different combinations of materials around the target have been studied which have an effect on shielding performance, but less so on DPA production. An optimum in terms of shielding is found by arranging a 30cm thick layer of lead around the target followed by 70cm of Polyethylene and 10cm of borated polyethylene, although this does exceed slightly the original specification for the maximum size of the installation (a cube 2 metres on a side). Naturally, decreasing the beam power is also beneficial and since an optimum for DPA production has been found between 200 and 400 MeV, the lower bound of this range would be preferred for optimal shielding. The case is illustrated in figure 12 below.

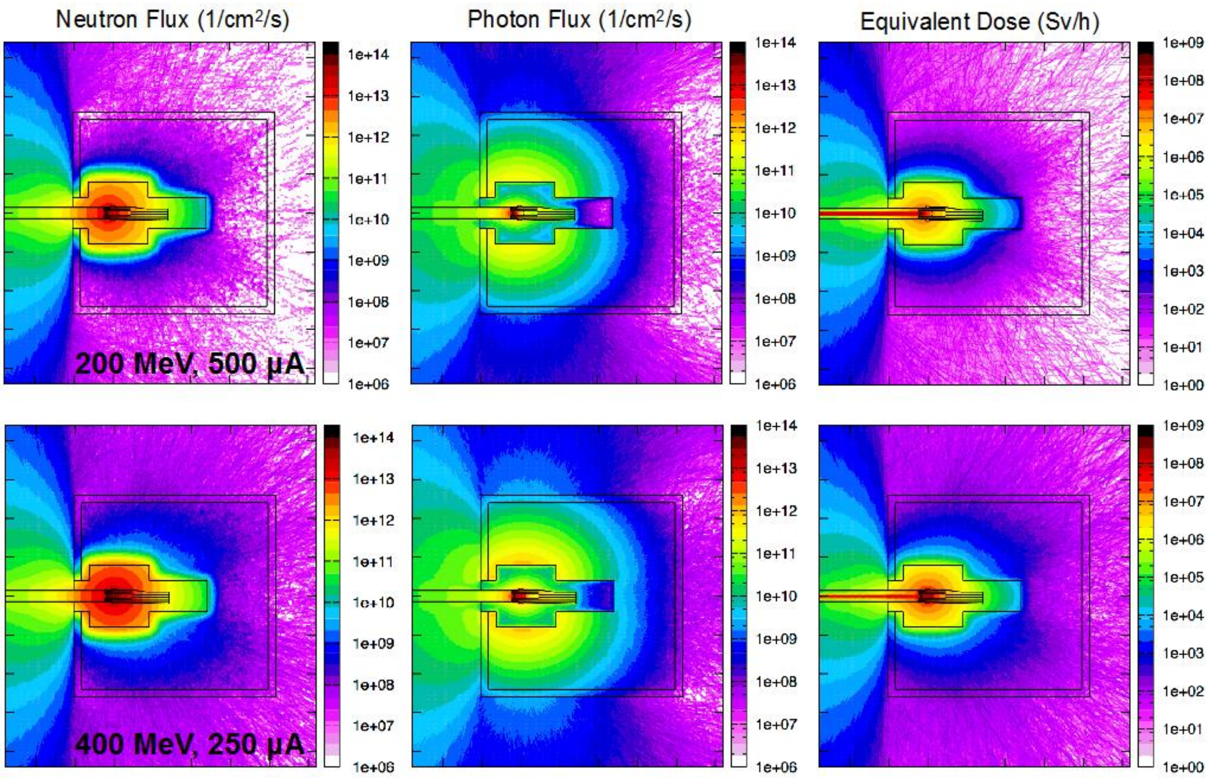

Fig 12. Neutron and photon fluxes (1/cm^2/s) and ambient dose equivalent rates (Sv/h) in the target and shielding, for 200 MeV (top) and 400 MeV (bottom) beams

3.7 Safety case and critical technologies

Detail analysis of the beam window in particular the thermal stresses, show that the margins, using conservative assumptions for the effect of material irradiation, are quite satisfactory; over 200%, see figure 13 hereafter. These margins are sufficient to guarantee safe operation over a complete test campaign, particularly as the window can be exchanged easily after each campaign without requiring the rest of the target to be dismantled as shown in figure 7 above.

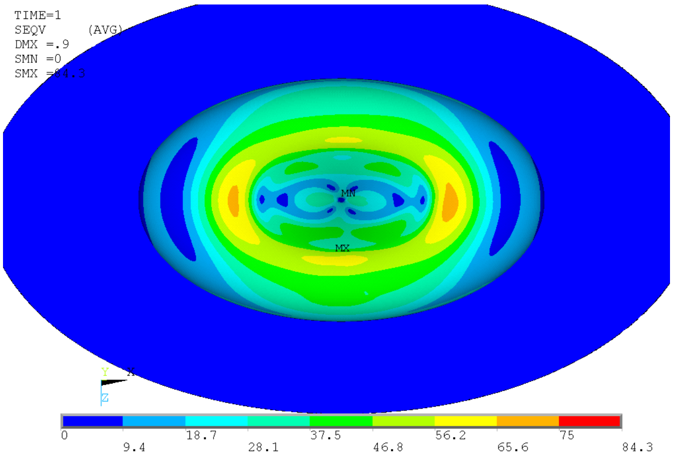

Fig 13. Von Mises thermal stresses [MPa] in the beam window

Thermal-hydraulic systems analysis with safety codes such as RELAP/CATHARE/NRC-TRACE has not been performed in [6]. It would be required for an assessment of all safety cases. However, the TMIF design integrates some inherent safety features which should cope with most foreseeable accidental cases.

For instance, in the event of a loss of the EMP a gradual coast-down of the liquid metal flow should occur until natural circulation conditions are reached, since the cold source is situated at the top of the loop and the heat source, the target, is at the lowest position in the loop. This should give ample time to switch off the beam before the reduced flow on the window leads to its failure.

Another type of accident, in which the primary circuit is perforated (Loss of Coolant Accident or LOCA) is also mitigated with a target in the lowermost position as it ensures that in all cases, the spallation zone, which absorbs the beam, will the last to be drained of liquid metal.

4. Proposed deployment

Continuation of the task is to be pursued in the context of a multi-national initiative aimed at building the proposed TMIF. Such a development can be shared between participating institutes to help funding; the construction of a first prototype is expected to cost 7.5 M€. Interested parties from Europe and Asia are being approached at the time of writing and more are invited to join. Work packages, briefly described in [6], would be allotted according to the experience of each participant with a view to minimising the need for interfacing.

The goal of a follow-on project would be to build a prototype in as short a time as possible, ideally three years, leading to a first irradiation test in an existing accelerator facility over a year. Thus first-hand operational experience would be readily available for an evaluation period, which would conclude this first operation. Further improvements may then be expected, leading to a mature design which could be standardised and adopted in accelerator facilities around the world for testing irradiated nuclear materials.

5. Conclusions

The EU FP7 TIARA research program has funded a design study for building a compact flexible facility allowing samples to be tested at high dose rates of up to 25 DPA per annum. The proposed design, designated by the acronym TMIF, would require an estimated 7.5 M€

in funding for full-scale development over a period of three years. The scope of materials which could be tested under high irradiation cover new materials for conventional Gen°III reactors through to projected Gen IV reactors and Accelerator-Driven Systems. The fusion reactor program currently undergoing development may also benefit, since it urgently needs reliable material data to justify the engineering choices needed in its construction.

Other developments for the proposed facility could be envisaged, such as the production of commercial-grade isotopes using an accelerator-based facility. In such a case, the samples inside the target would be replaced with isotope-laden fluids running through pipes in an area of high neutron-flux in order to activate substances such as Mo99 for technetium production. The possibility of choosing the ratio of proton / neutron activation could be of benefit in terms of tailoring the isotopes to a dedicated medical use.

6. Acknowledgements

The research leading to these results has received funding from the European Commission under the FP7-INFRASTRUCTURES-2010-1/INFRA-2010-2.2.11 project TIARA (CNI-PP). Grant agreement no 261905.

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