TIARA-REP-WP9-2012-001

Test Infrastructure and Accelerator Research Area

Status Report

Report on the Definition and Specifications of the Irradiation test Facilities

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TIARA Project

Work Package 9: TIHPAC - Test Infrastructure for High Power Accelerator Components TIHPAC

Task 9.1: Multi MW Irradiation Facility for complex target testing

Milestone n◦ M 9.1: DSIF Report on the Definition and Specifications of the Irradiation test Facilities

Planned Date (month): ***12***
Achieved Date (month): ***12***
Lead Contractor: ***CERN***

Project acronym:	*TIARA*
Project full title:	*Test Infrastructure in Accelerator Research Area*
Start of the Project:	*1st January 2011*
Duration of the project:	*36 Months*
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1 Technical context

The current report covers milestone M9.1 in Task 9.1 of work package 9 of the TIARA project. The objective addressed by the work package 9 focuses on planning the infrastructure necessary for testing high power neutron spallation targets. There has been extensive research and significant progress in this area in recent years and more needs to be done to prepare for the full-scale testing of these complex components.

The objective of the first task 9.1 in the work package is at first to identify the necessary test facilities that are required to address several technological issues raised by the development of a multi-MW target. In a second step, task 9.2 will perform a design study of the final target complex irradiation facility at high power. These separate issues are addressed in two tasks as defined in the table below namely the specification and the design of the facility. The two tasks are closely connected.

Summary of task and sub-task breakdown		
Task	Short Name	Description
9.1	**M-MWIF**	**Multi MW Irradiation Facility for complex target testing**
9.1.1	DSIF	Definition and Specification of the Irradiation test Facility
9.1.1.1	*IIF*	*Identification of the Irradiation test Facility*
9.1.1.2	*SIF*	*Specifications of the Irradiation test Facility*
9.1.2	DSIF	Design Study of the high power Irradiation test Facility
9.1.2.1	*PDIF*	*Preliminary Design study of the high power Irradiation test Facility*
9.1.2.2	*TDIF*	*Technical Design report on the high power Irradiation test Facility*

Deliverables				
Num	Nat	Short name	Description	month
D9.1	R	TDIF	Technical Design Report of the Multi-MW test Irradiation Facility	36
Milestones				
M9.1	R	DSIF	Report on the Definition and Specifications of the Irradiation test Facilities	12
M9.2	R	PDIF	Preliminary Design report of the high power Irradiation test Facility	16

Current report

As a first step towards defining the needs for such a development, the state-of the art and the applications of science and technology in the field of high-power neutron source development will be examined. Both existing facilities and projects in the pipeline due to come on-line in the next 10 years will be considered.

A summary of the characteristics of these facilities specifically with regards to the neutron source will be derived and used as a set of parameters for the facility being planned.

1.1 Addressing the task by building on existing experience

The work package task to develop a dedicated irradiation facility builds on prior work funded by the EU FP7 program, the EURISOL Design study, which studied the feasibility of an advanced isotope production facility. The target complex was one of the key elements of the EURISOL facility, which was the subject of intense design work and preliminary prototyping phase in the EURISOL Design-Study. It is therefore one of the key reference projects which are to be used in defining the specification of a future high-power irradiation test facility.

The 4 MW mercury neutron spallation source was to be set up in a target station where it would be utilised in conjunction with a uranium target to create exotic isotopes by rapid fission. The converter was based on a circulating metal loop exposed to direct proton beam irradiation. First prototypes were developed and tested off-line, from which relevant experience was gained. At the present stage, several issues are yet to be addressed, such as the impact of beam irradiation parameters on the liquid metal loop operation. Likewise, the target development will necessitate further research in the field of heat exchange with liquid metal, irradiation, corrosion and fatigue testing of materials.

Achieving the design of a EURISOL class target will require several tests: first of sub-components, instrumentation tests, and finally full scale tests. In order to better ascertain the needs for testing a high-power target, various existing and projected facilities will be examined, their characteristics evaluated leading to a final specification for a high-power testing facility. Not all parameters may be defined precisely, but a framework can be defined The process is outlined below.

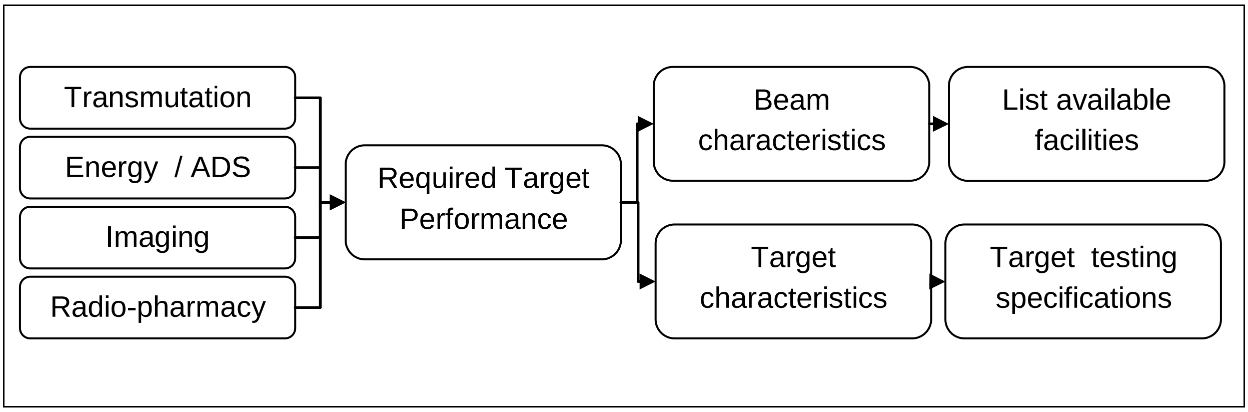

Figure 1: General considerations for defining the testing requirements

1.2 Moving forward to the next stage

The TIARA project is aimed at giving centre stage to accelerator developments and promoting their use in a way that is innovative and offers multiplies advantages to society by seeking cross-cutting cooperation with multiple partners.

The objectives are summarised in the table below and expounded on in the following paragraphs.

Objective	**Strategy**	**Relevance**
1. Establish a sound scientific & technical basis for the safe long-term management of hazardous radioactive waste	The technology developed in this program could if scaled up be used in an ADS type actinide burner	**3**
2. Promote safer, more resource-efficient and competitive exploitation of nuclear energy	Replaces a reactor, but it is still a nuclear application	**1**
3. Ensure a robust and socially acceptable system of protection of man & the environment against the effects of ionising radiation.	Waste is reduced compared to a reactor but not entirely eliminated, medical waste is a growing problem	**2**
4. Promote a true “European Research Area” in nuclear science and technology	Project unites nuclear establishments and companies in three countries	**1**
5. Support for EU policy initiatives, SET-Plan, Energy Policies and Nuclear is a very low carbon technology	By replacing a reactor with a facility consuming less than 5 MW, the energy demand is reduced	**1**
Evaluation criteria		
6. Main criterion: scientific and technical excellence	Scientific experience from institutes such as CERN and industrial experience	**1**
7. Range of funding schemes promoting integration	Commercial applications leading to long-lasting relationships between industrial partners and state research institutions	**3**
8. Shared cost & leverage effect of EU funding	Benefit from on-going physics projects at CERN and associated labs	**1**

Table 1: Evaluation of strategic priorities covered in the task

1.3 Task objectives

1.3.1 Encouraging sustainability

The underlying rationale for developing high power neutron sources is to make nuclear technology more sustainable, By using an accelerator, a neutron source and a blanket for the production of isotopes, operations are simplified, nuclear waste is minimised which facilitates licensing by focusing on a safety-first approach. All these objectives are high on the list of priorities set up by the EU to foster new approaches in the nuclear field. Potential economic benefits include increased competitiveness from innovative “made in EU” technology as well as socio-environmental impacts which will be described in detail in the dedicated chapters.

A new approach is needed to nuclear technology placing sustainability in the forefront. This is the goal of TIARA which seeks to make a contribution to this goal with accelerator-based technology

1.3.2 Consolidating research results

Results from previous undertakings by research institutes across Europe funded through the FP6 program have proven the theoretical and experimental basis for high-power spallation neutron sources. Two such programs, Megapie[1] and Eurisol[2], have played a fundamental role in articulating the case for continued technological development in this field with a view to practical industrial applications.

The project aims to draw on many years of experience in the development of neutron sources to build a powerful and compact reliable neutron source. The envisaged applications of such device are:

- irradiation facility for nuclear materials,
- transmutation of radioactive waste and ADS system development.
- medical isotope production from accelerators,
- imaging techniques for fundamental research,

The project’s goal may best be achieved by applying and simplifying previous experience from FP4/ FP6 funded programs, notably TARC in 1997 which proved the feasibility of coupling a neutron source with a blanket, Megapie in 2006 the world’s first irradiation of a liquid metal source and Eurisol in 2009 which validated a compact source. The objective is to develop a neutron source, which compared to previous experimental devices, has the following advantages:

- is compact, safe and reliable to operate close to major urban centres,
- uses established technological choices that can be licensed,
- provides an alternative to dedicated research reactors.

Neutron sources are essentially metal targets which send out a shower of neutrons when the nuclei of the target are hit by protons sent 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.

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[1] http://megapie.web.psi.ch/

[2] http://www.eurisol.org/site02/index.php

The neutrons produced in the source may be used either for fissioning fissile materials to produce isotopes and energy, or for transmutation using neutron capture and also to test materials under irradiation.

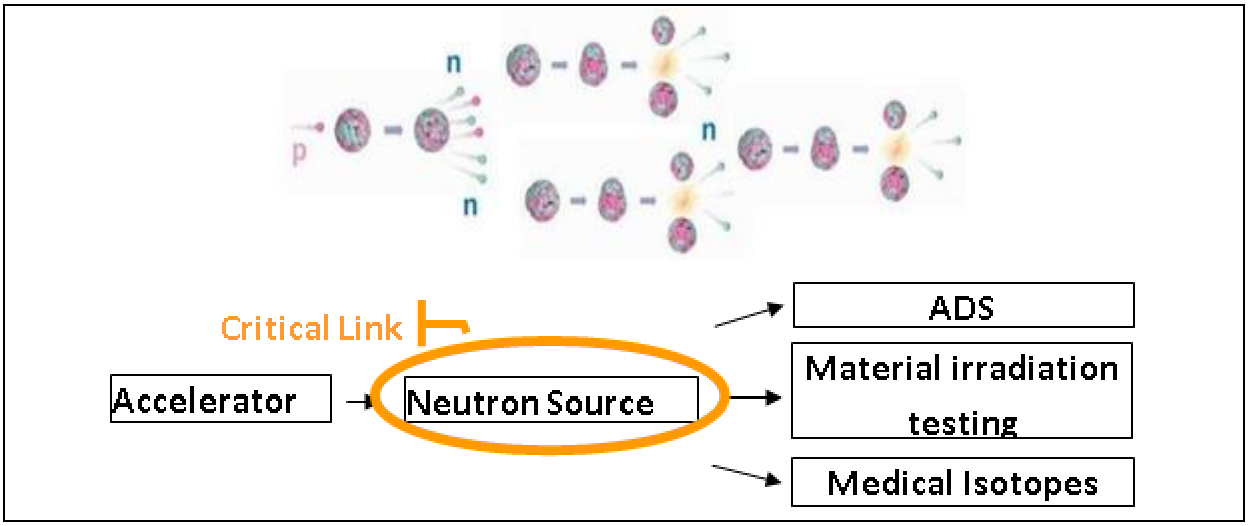

Figure 2: Spallation reaction (top). Uses of spallation sources (bottom)

In parallel to the source, an associated blanket will have to be developed, with which it is possible to make best use of the neutron flux produced in the compact neutron source. The precise nature of this blanket is not included in the current work package. However the overall systems requirements in terms of shielding will be derived to provide an adequate design of the target station.

The whole thrust of the work is therefore to demonstrate that it is feasible to develop a test irradiation facility coupling an accelerator with a neutron spallation source, that such an infrastructure can be built easily and economically with established technologies and that it can serve for a variety of applications in nuclear physics. The neutron source and its surrounding equipment are the critical link still needing development and testing in cooperation with industry

1.3.3 Fostering links with industry

In terms of overall methodology, the two distinct subtasks mentioned in the introduction correspond to successive stages and are articulated in such a way to present a logical development in the work package; firstly identifying needs, secondly planning the infrastructure required to address these needs.

Amongst the objectives of the current work package, industrial networking is seen in itself as an organisational objective; a reliable link to capable and willing industrial partners must be set up which can be relied upon later in the construction phase. Such a complex technological project may best be supported in practice by adopting an industrial approach to the development of scientific infrastructure; uniting industry and nuclear research institutes to develop a neutron source and surrounding equipment in a compact facility for a wide variety of purposes.

1.3.4 Applying research results to large research facilities

The developed technology will thus have undoubtedly strong potential to be applied to larger scientific facilities currently under construction, such as the Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) in Mol or the European Spallation Source (ESS) in Lund. Future developments such as Eurisol are also of interest. A consequence of the industrial compact approach is that the design will be easily scalable to meet the needs of other potential customers such as large planned facilities (MYRRHA) for the purpose of nuclear material investigation and waste transmutation or ADS research.

2 High-power Neutron Source Applications

There are many possible applications of accelerator based technology which can potentially benefit from the technology development being proposed in this work package. The following have been envisaged in the scope of the current work:

- Sub-critical reactor for energy generation
- Radioactive waste transmutation
- Imaging techniques for molecular technology and nanotechnology
- Radio pharmacy

It is therefore necessary to gauge the current state of these industries so as to assess the essential parameters of the future accelerator-based facility. Only then is it possible to plan the next logical steps necessary towards establishing a ***testing facility for accelerator-based applications.***

2.1 Current state-of-the-art in the application areas

2.1.1 Sub-critical reactor for energy generation (projected state)

The initial concept put forward by Nobel prize laureate Carlo Rubbia and diversely known as Energy Amplifier, Accelerator Driven System or Rubbiatron centres on the development of a new type of nuclear reactor which is inherently safe by placing a central high power neutron spallation source (or target) driven by an accelerator at the centre of a sub critical core incorporating either classical Uranium or preferably) proliferation-resistant Thorium.

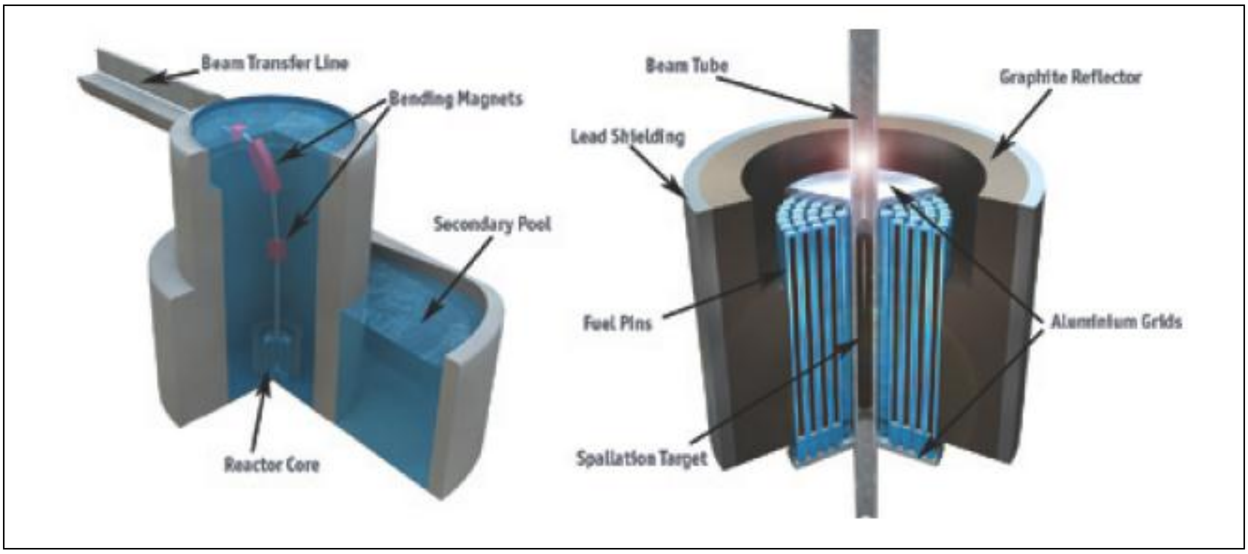

Figure 3: Schematic of an ADS (left) and detail of the core (right)

Ref: “Towards an Alternative Nuclear Future” by the thorium energy amplifier association, 2009-2010

The fundamental requirement on such a neutron source is that it be as compact as possible, with a high power in the MW range and inherently safe. The thermal power of such a reactor design has been proven to follow the relation:

$P_{therm} = P_{source} / (1 - k_{Eff})$

Where: P_{therm} = Thermal Power output of the reactor

P_{source} = Power of the beam impacting the neutron source

k_{Eff} = criticality coefficient of the core

For instance a $k_{Eff} = 0.95$ will multiply by 20 the power emitted by the beam. If one assumes a 5 MW beam, the thermal power output by the reactor will be 100 MW, sufficient for a prototype.

Advanced studies of advanced neutron source concepts such as EURISOL have allowed some essential parameters to be derived for the neutron source which may be used in an ADS reactor prototype of the type shown above in figure 3.

Parameter	Value	Unit
Proton Energy:	1	GeV
Beam Power:	5	MW
Beam Current:	5	mA
Beam σ–width:	< 2.5	cm
Peak neutron flux:	10^{15}	n / cm^2 s
Neutron emission rate:	10^{18}	n / s
Neutron Source Diameter:	< 30	cm
Neutron Source Diameter:	> 60	cm
Peak Heat deposition:	10	kW/cm^3

Table 2: Parameters of an ADS Beam & Neutron Source

There is increasing interest in this technology, the Norwegian group AKER launched a study in 2010, the spin-off was subsequently resold to Jacobs Engineering in the US as part of a restructuring drive away from nuclear on the part of the Norwegian group. Since then the Australian government has taken intense interest in this technology, with recent intervention in parliament proposing Australia invest in a technology that is inherently safe, proliferation resistant and makes better use of existing natural resources in that country.

2.1.2 Waste transmutation (projected state)

The idea outlined above may also have a second application as it provides an intense source of neutrons configured to irradiate nuclear materials, it could also be used for transmutating nuclear waste and reducing its toxicity. In this case, the fuel core surrounding the neutron source is replaced by a special mixture of fuel and actinides separated from high-level nuclear waste.

In this manner it may be possible to reduce the amount of high-level waste requiring deep geological deposition, a very costly option. Studies have concluded that by chemically separating the long-lived actinides from the spent fuel it may be possible to reduce the time needed to return the radioactive material to background levels form hundreds of thousands of years to a few centuries, with an accompanying decrease in the activity of the waste when it enters the disposal site. Both these long-term and short term effects entail that it may be possible to envisage surface-storage for much of the waste currently intended for deep geological storage.

The requirements on the neutron source and accelerator for such an application are broadly the same as in the case of an ADS dedicated to energy production, as the main difference centres on the type of fuel being used and the nature of the blanket used to optimise the exiting spallation spectrum of the neutrons.

2.1.3 Radio-pharmaceutical industry (realised and projected state)

The state of the art in Radio Isotopes relies on production inside dedicated nuclear reactors. However, since 2009, several sources confirm that the isotope production has gone through an important crisis and adequate viable long-term solutions have not been fully identified.[3].

Neutron irradiation of U235 targets for the production of fission products for medical application is carried out in a small number of ageing research reactors. All the production of radio-isotopes (RI) for North America takes place at NRU, a research reactor on Chalk River (Canada), dating back to the 1950s.In Europe, production is concentrated at a small number of research reactors: HFR (Petten), BR2 (Mol) Osiris (Marcoule) and ŘEŽ (ČZ). Production reactors are also found in South Africa (SAFARI) and Australia (OPAL).

The present reactors used for medical RI production are research reactors, paid by public funds for the purpose of research in nuclear technologies. RI production was not intended to be their primary mission and is charged at marginal (minimal) cost. This situation has led to an impasse that is not sustainable in the long run, both in financial terms and with regards to its security. If on the other hand several small accelerator-based facilities were to become operational around Europe in the main regional centres, possible disruptions of production could be avoided and distribution of RI would be facilitated as well as European self-sustainability and competitiveness improved.

The previous considerations demonstrate that the industry is due for a fundamental change in production methods. All the characteristics for a rapid change are present, in view of the lack of the response to the following challenges:

- there has been no change in production methods in over 50 years
- there is pent-up demand on a global scale
- the regulatory environment is evolving rapidly due to environmental concerns
- financial burdens on state health budgets are putting pressure on prices
- flexibility and dependability are demanded

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[3] *From presentation ADONIS, A Cyclotron driven neutron multiplier for the production of Mo 99, Yves Jongen, 37th ECPM*

Some attempts have already been made to gauge the potential for accelerator driven production of isotopes. In 1995, ADONIS (Accelerator Driven Optimized Nuclear Irradiation System) studied theoretically using a 150 MeV x 1.5 mA = 225 kW of proton beam impacting a tantalum target producing a neutron flux of 7.5 10^{15} neutrons/second. The neutron flux would have resulted in 700 kW of fission power in standard HEU isotope production targets surrounding the neutron target. A weekly production of 5´000 Ci of Mo99 (post calibrated 6 days EOI) was predicted.

The gap with accelerator-produced Mo99 is therefore still in favour of reactors. However,

- the costs were calculated based on production rates in an experimental device for the accelerator-based facility, which has not been optimised.
- The cost of waste disposal is not accounted for in the nuclear reactor case

In order to increase the economy of the accelerator-based facility, a more compact source may be developed allowing closer bundling of the isotope targets to locate them inside the high flux region. It appears that no industrial solution exists for producing a compact flexible neutron source. However there is enough prior experience to develop an industrial product suitable for the purpose of producing isotopes in a novel, safe and sustainable manner as will be outlined in the following. The magnitude of the neutron emission rate is however significantly less that in the previous case for energy production and waste transmutation.

- ADS / Waste transmutation: 10^{18} n / s
- Decentralised radio-isotope production: 10^{15} n / s:

Given that the strength of the neutron emission rate is roughly proportional to the beam power, a reduction factor of roughly 1000 can be applied to the previous parameters in Table 2. However as most medical accelerators operate at best in the 70 MeV range for which the neutron yield per proton will be lower, hence a power of at least 100-200 kW should be aimed for, rather than the 5 kW range that would derive from simply factoring the relative neutron flux of the two types of applications.

In addition the heat deposition in the target should be as close as possible to 10 [kW/cm^3], as mentioned for the ADS/Waste transmutation applications in order to deliver the same magnitude of density flux. Depositing the beam power with less density would reduce this flux and thus increase neutron losses. Such considerations influence the design as follows:

- a source with the smallest possible diameter to increase the neutron flux, which will result in a heat deposition rate of up to 10 kW/cm^3.
- a source operating with a 70 Mev/ 200 kW beam resulting in a neutron production rate of at least around 10^{15} n / s:

2.1.4 Imaging techniques for molecular technology and nanotechnology (realised state)

There are currently several publicly funded laboratories in the world offering imaging techniques on a nano-scale to explore the potential of designing at the molecular level new drugs, new materials, and new information-technology devices. These institutes such as the

Oakridge NL Spallation Neutron Source (US), the Institute Laue-Langevin (F), the Paul Scherrer Institute (CH), J-Parc (JP) or ISIS (UK) have now well over 20 years' experience in the use of neutron imagery and associated techniques.

Essentially the experimental devices being used in these various institutes rely on closely collimating the neutron flux exiting the source of neutrons in order to achieve the highest possible quality observations. This is achieved by allowing a small portion of the neutrons to exit via beam tubes and collimators to ensure the neutron flux is directionally homogeneous and then running the escaping neutron through monochromators to select the energy/ range of interest. Inevitably the process leads to a considerable decrease in magnitude of the flux in order to guarantee its purity. An example is shown below for the Trics experiment used in the analysis of polarisation and magnetic states for advanced alloys that are being studied for instance to advance supra-conductivity.

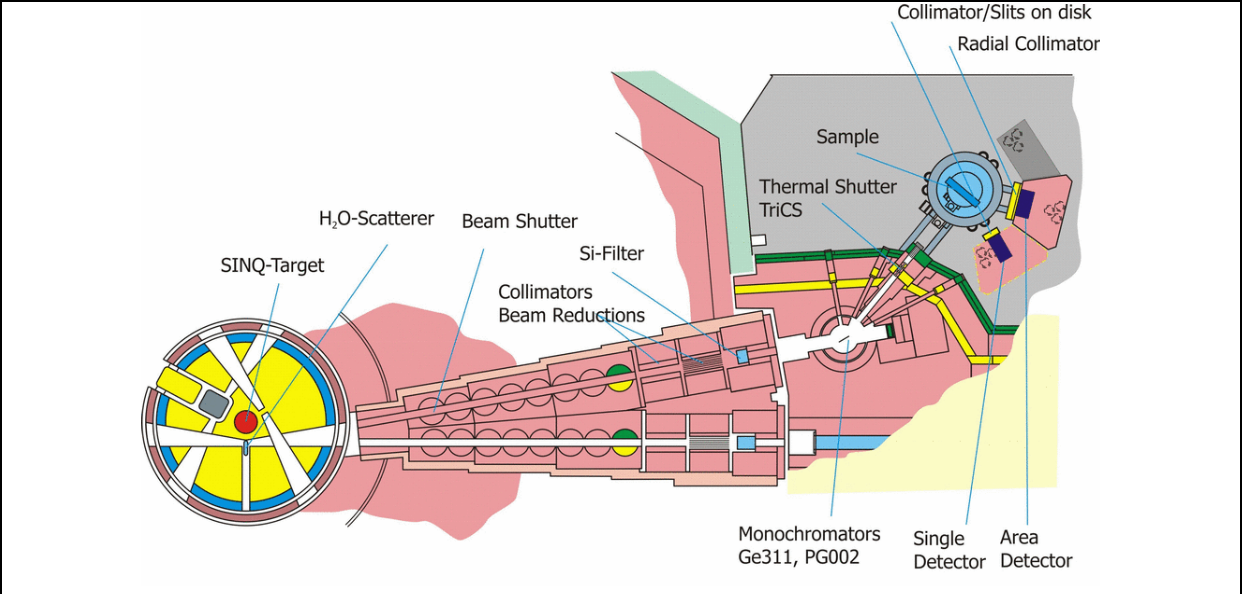

Figure 4: Experiment TriCS Layout at PSI. Ref.:http://www.psi.ch/sinq/trics/description

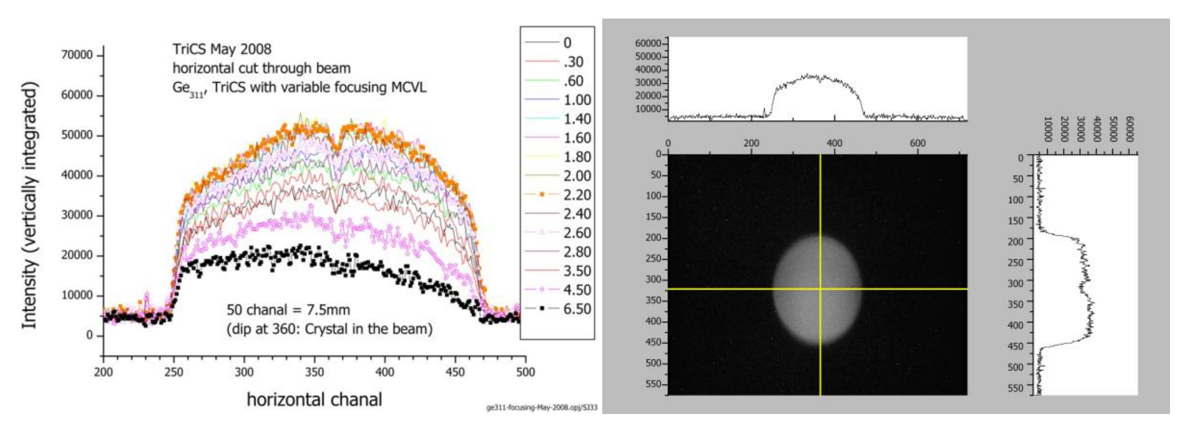

Figure 5: Collimation of the neutron beam along one axis (left) and two axis (right)

Observing the layout of the experiment in the figure above it is obvious that two factors will increase the flux and hence the quality of the measurements; positioning the instruments closer to the source and increasing the strength of the source.

However in the SINQ layout, the neutron beam is not pointing radially at the source. This is due to the characteristics of the moderation in SINQ which is realised by the large D2O tank surrounding the central source. By arranging the beam tube tangentially to the source, the high energy part of the neutron spectrum is filtered out of the neutron beam as it has no direct line-of-sight. This is a benefit as it would perturb the quasi-monochromatic properties that are demanded of the neutron beam in well-defined energy bands that are well below the peak spallation energy of 10-30 MeV exiting the source. The neutrons entering the beam tube have thus already been subject to diffusion (but also some lost to capture) and are lower in energy but highly heterogeneous spatially as they have been diffused by the D2O in the tank surrounding the source. They can only be collimated after multiple collisions in the beam tube which results in high losses to the instrumentation at the other end.

It would therefore be highly beneficial to the development of neutron sources if it were possible to develop moderating and collimating beam tubes that were able to make a better use of the neutron production, by having the end of the beam tube that is pointing at the source gather as much of the neutron flux as possible before adjusting the neutron flux collimation and energy inside the beam tube. Thus losses before the neutrons enter the beam tube would be lessened.

In practical terms this could involve a change in the overall layout bringing the beam tube as closely as possible to the source and having the highest possible flux at the source surface, thus reducing the source diameter as much as possible. In such a way, the source-end of the beam tube would capture within a small surface a larger neutron flux. It would also seem advantageous to develop a neutron source without water cooling to avoid affecting the neutron production within the source, before the neutrons enter the beam tube.

The requirements derived from the imaging application can therefore be summed up as influencing the design as follows:

- a neutron source with the smallest possible diameter
- a neutron source with no moderating fluids for cooling

2.2 *Mapping and description of existing solutions in relation to neutron sources*

2.2.1 The SINQ at the Paul Scherrer Institute (PSI)

Advanced spallation neutron sources are currently used for research at various institutes around the world (MEGAPIE at SINQ in Villigen Switzerland, JSNS in Hokkaido Japan and SNS in Oakridge USA). Current efforts are aimed at improving flexibility with new planned facilities such as MYRRHA and ESS, with a natural bias towards the fundamental sciences. Many diverse scientific users need to be accommodated, which makes it a challenge to optimise the facility with a single-use focus such as radio-pharmacy. The figure hereafter shows how complex the machinery of such large facilities has become in order to accommodate all users, using the example of SINQ at PSI.

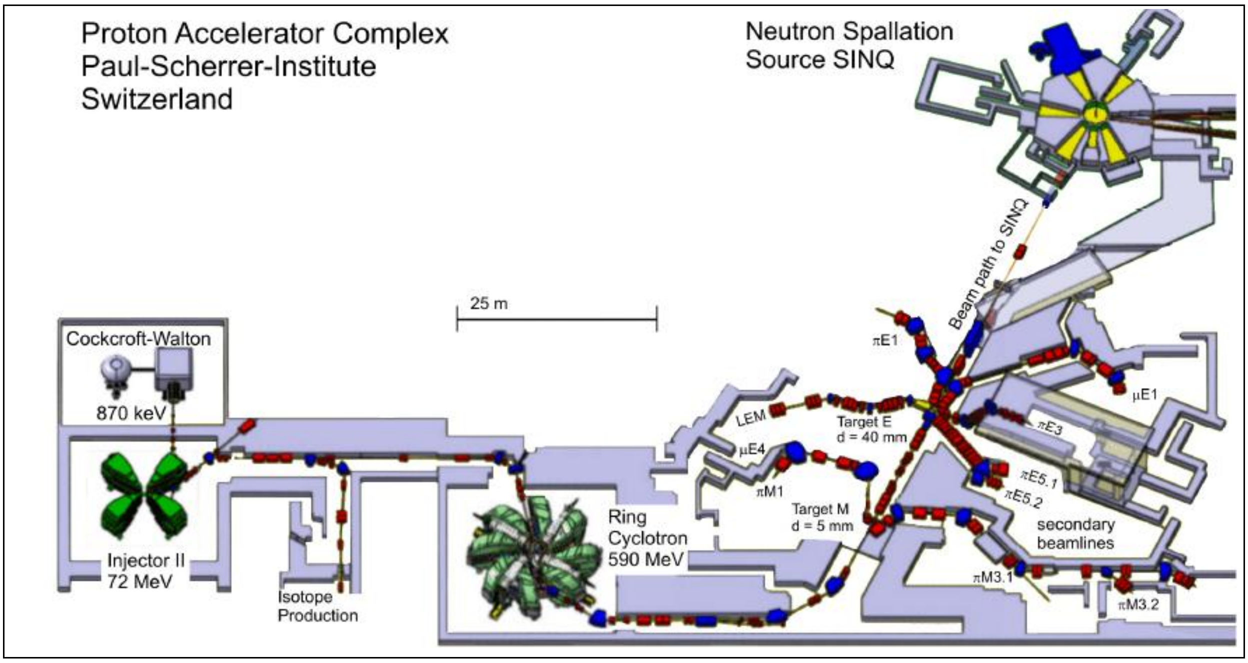

Figure 6: Existing facility SINQ at PSI

The facility uses for the spallation target as a standard solution based on solid metal technology. This consists in Zircalloy tubes, 10mm in diameters filled with lead and cooled by heavy water. The rods are bombarded by a proton beam and emit spallation neutrons which are then emitted radially, traversing several centimetres of moderating D2O. Since the source is placed in the centre of a D2O tank, 2 metres in diameter, the neutron spectrum is significantly moderated within the thermal and epithermal region. The spallation target which constitutes the central component of the SINQ neutron source is pictured below in figure 9. The rods are held in place by a rectangular structure which serves at the same time as a physical separation between the cold down coming DO2 along the inside and the hotter fluid flowing back up between the rods in the opposite direction.

The operational experience accumulated so far has shown this type of source is reliable, safe and relatively easy to manage in terms of radio-protection although there have been instances of rods rupturing due to the heat load. This has led to the contamination of the cooling fluid with spallation products from the lead contained in the tubes. Another concern is the case of over-focusing of the beam which can burn through the rods containing lead. Since the lead is liquid under operation a reaction between liquid-metal and water could ensue triggering a sudden pressure increase. The cooling system is fitted with pressure relief valves to cope with this problem. The danger of over-focussing has been reduced by multiple sensors which constantly monitor the beam and are linked to a fast shut-down system.

In recent years, the accelerator at PSI has been constantly upgraded, such that the power deposited in the rods has been steadily increasing, the limit seems to be around 1.2 MW beam energy and a power density in the rod of around 1 kW/cm^3 beyond which the configuration would be difficult to cool.

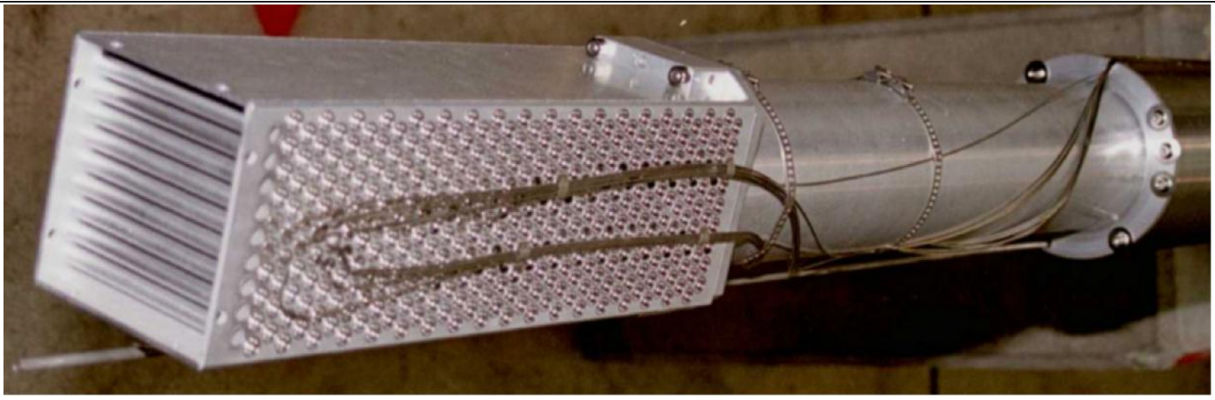

Figure 7: Operational solid target for the neutron source SINQ at PSI

2.2.2 MEGAPIE at PSI: the world's first Megawatt-class liquid metal spallation source.

The development of Megapie culminated in 2006 with the world's first irradiation of a liquid metal source operating successfully under a 1 MW beam for 4 months. The production of neutrons was thereby increased by 80% under a continuous beam, and was found to be close to 10^{14} n/cm^{2}s at the surface of the target, an 18 cm high cylinder with a proton penetration depth of 27 cm.

Thus the total yield of spallation neutrons approached 10^{17} n/s. Thus In terms of production capacity, neutron sources using liquid metal technology have shown they have the potential for closing the gap with conventional reactors at close range, in the vicinity of the target due to the 1/r^2 rule for the neutron flux which weakens the flux further away from the surface.

Liquid metal technology although not insurmountable, did pose some major challenges in terms of safety. The necessity to integrate an existing facility led to some difficult compromises rendered necessary by the lack of space. Indeed all the systems had to be packed within a cylinder roughly 4 metres long and 40 cm in diameter narrowing down to 20 cm at its lower end (ref. figure below). The solution chosen by the team was to enclose the liquid metal loop within the cylindrical body of the neutron source as it would be activated and to extract the heat with an intermediary internal heat exchanger (shown in blue in the figure below), which would then pass on the heat to an external heat exchange responsible for evacuating the heat outside the facility. In this manner, multiple confinement barriers were built in between the source of radioactivity and the environment.

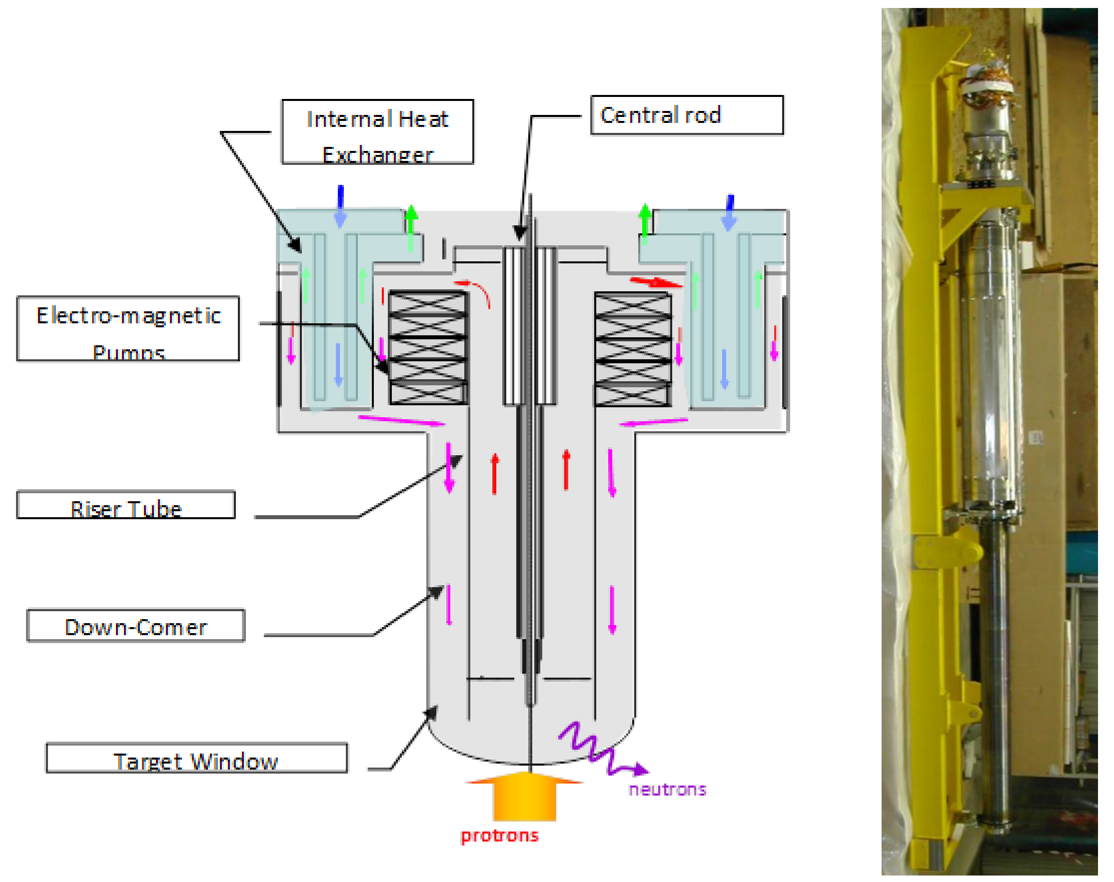

Figure 8: MEGAPIE LM Neutron Spallation source. Schema (left) and hardware (right)

Radio-protection and confinement of radio-active substance were problems needing to be addressed as the liquid metal once irradiated by the proton beam contains polonium. Subsequent analysis of the products in the liquid metal, post irradiation test proved that the polonium remains bound to the liquid metal and does not sublimate for temperatures below 600°C (Neuhausen et. al 2011).

Another challenge was the evacuation of heat from a tightly confined space. Megapie achieved this goal with a highly efficient heat exchanger Diphyl which proved to be unwieldy in a radioactive environment due to its organic nature. Thus future heat exchangers should use more neutral fluids such as light/heavy water or low-melt liquid metals such as gallium.

Finally the safety case in relation to external events such as earthquake, external impacts, fire proved also difficult to tackle, in part due to the fact that Megapie had to integrate an existing facility for which it was clearly not optimised. Thus the proton beam orientation penetrating the target form below should also be avoided in the future as it poses some serious concerns for all manners of external events.

The confinement strategy proved particularly successful when the heat exchanger started leaking an organic gas into the safety hull. This may be seen in the picture below as a red curve increasing steadily with irradiation time and then decreasing when it was vented to a decay tank during brief shutdowns. Although the design fault in the heat exchanger was a failure, the success of containing the ensuing gas was a vindication of the strategy adopted.

Another gas that had been expected (pink curve) was caused by the spallation reaction which raised the pressure of the cover gas at the top of the target. A cold trap had been foreseen which did not fully meet expectations.

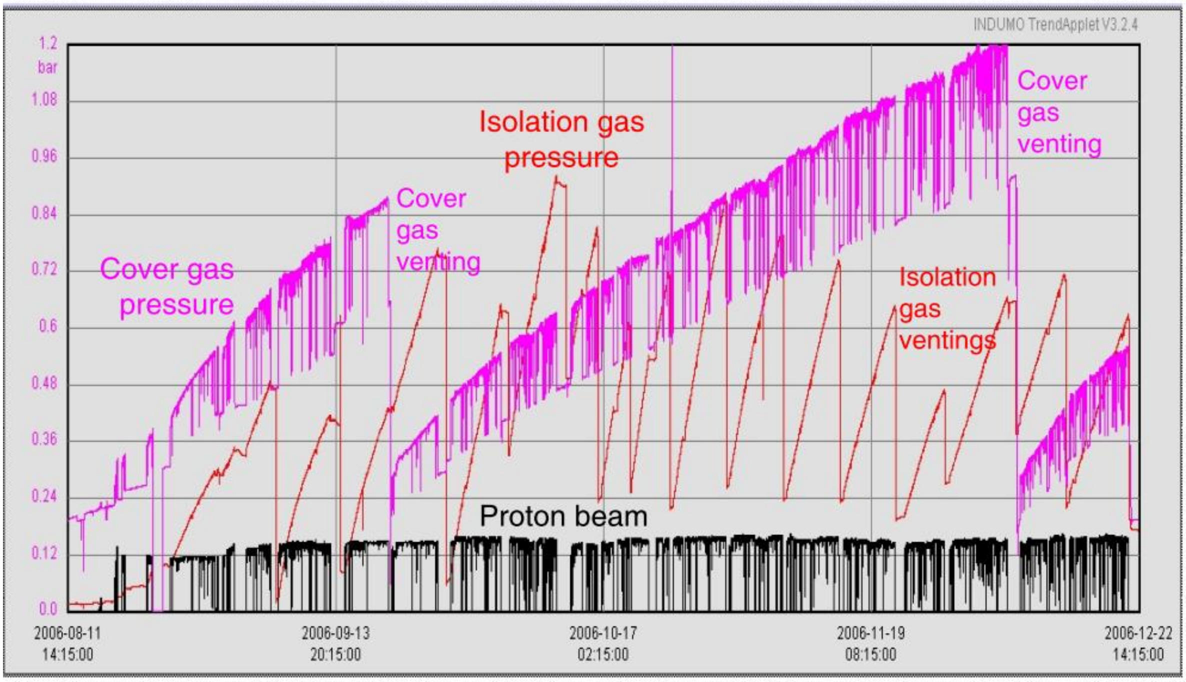

Figure 9: MEGAPIE operational measurements

Therefore containment strategies are crucial to the successful operation of neutron sources and built-in connections must be planned to ensure in-situ analysis and subsequent evacuation of fluids and gases and their proper treatment if they are contaminated

2.2.3 EURISOL - A 4 Megawatt capable liquid metal spallation source.

This first irradiation of a liquid metal neutron source Megapie was followed in 2005-2009 by the design and hydraulic test in 2009 of a full-scale mock-up of a more powerful target, Eurisol. This later design demonstrated it had the potential of increasing the beam power to 4 MW, which would produce a considerable increase in neutron flux. The Eurisol program was funded by the EU up to the design validation level for the scientific purpose of producing rare isotopes for physics; the capacity for absorbing a 4 MW beam was thus proven by a dedicated full-scale hydraulic test, however it was not irradiated due to the much shorter timeframe of the program, the project is under review by the EU for further development. It should be noted that 4 MW of beam power is the level needed for a demonstrator type ADS prototype as proposed by MYRRHA.

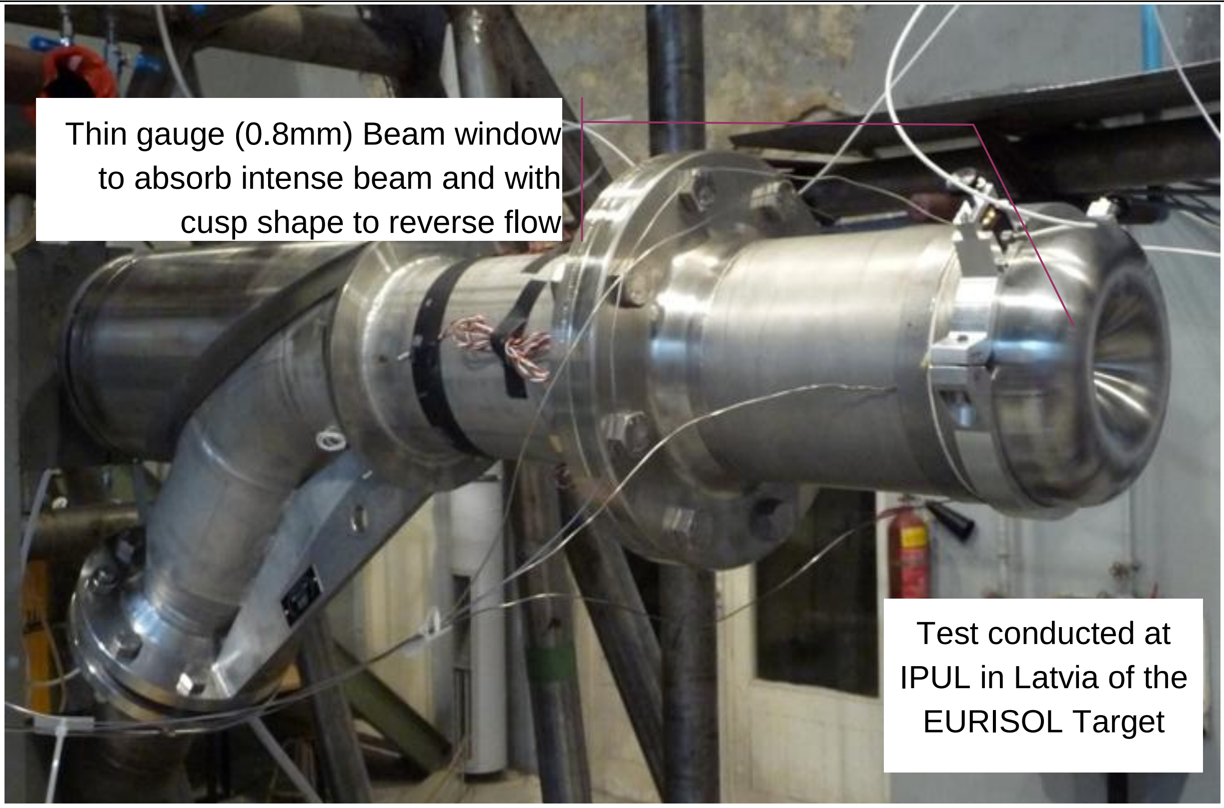

Figure 10: the 4 MW EURISOL compact high power on hydraulic test bench

A number of operational problems surfaced during the hydraulic testing of Eurisol. Notably the instrumentation was unreliable in respect of the flow measurement, a problem which had already arisen during the testing of Megapie. Both flow meters were dependent on the measurement of electromagnetic fields as their properties vary with the velocity of the liquid metal. However external influences such as interference from the electromagnetic pumps or temperature made the operation of such flow meter rather haphazard. A flow meter based on a more robust measurement technique should be developed.

The hydraulic testing of Eurisol concluded successfully but was limited to testing at low temperature, no heating was conducted. As such it would be necessary to check that the thin-gauge window which survived hydraulic testing successfully is also capable of shedding the heat deposited by a proton beam. There are two ways of simulating this effect,

- heating the window externally by impacting it with a spot form a 10 kW laser and measuring the temperatures on the window surface and in the liquid metal
- heating the liquid metal before it enters the target cooling the window externally with forced air convection and measuring the temperatures on the window surface and in the liquid metal

A more advances option would consist in electromagnetic induction heating to deposit large amounts of heat inside the volume of liquid metal where the proton beam is to deposit its energy. This has proven effective for testing solid targets but it may be a challenge in the case of liquid metal which is fluid and electrically conductive. The effects of the Biot-Savart induction force may prove to disturb the regular flow of liquid metal. However induction works at very high frequency typically MHz, therefore the fluid may not have the time to react to such rapid changes. This may have to be checked in a sub-scale experiment.

The neutron source used for Megapie and Eurisol both contained liquid metal. The experience from both these experiments is of particular value for deriving a safer reliable high-power spallation neutron source. As illustrated below, the two sources each explored advanced aspects of this technology.

Megapie was the first source operating with liquid metal under irradiation. Eurisol explored high velocities with liquid metal on very thin surfaces for the beam window allowing higher heat depositions and therefore a higher neutron flux. The lessons learnt from this experience are summed up below.

Relevance	Lesson learnt
System	Multiple containment strategy is vital Natural circulation is of little value Leaks must not flow into the path of the beam Leak analysis and mitigation strategy in place No organic cooling liquid inside source Development using multi-physics analysis
Component	Calibrated electro-magnetic pumps are reliable High-grade finishes reduce drag losses T91 /316 stainless steel are an appropriate choice
Signal	Diversify flow-meter instrumentation Instruments in- and outside of source (beam) Ensure leak detection using diverse sensors Pressure transducers and TCs are resilient

Table 3: Summary of Experimental feedback from Eurisol and Megapie programs

Ref. : K. Samec ICCAP Nice 2010

The lessons learnt indicated that a liquid metal target, although more complex, is undoubtedly an avenue worth investigating. It offers the possibility of allowing a more compact design through a far high power deposition whilst at the same time retaining much of the activity with the liquid metal. This last topic was the subject of a detailed investigation in the post-Megapie phase, which indicated that unless high temperature were attained, there was no danger of any release of Polonium, it remained bound to the Lead-Bismuth Eutectic.

2.2.4 MYRHHA - A Multipurpose research spallation source.

The Belgian government is leading efforts to develop a new research facility centred around a 5 MW facility. The engineering details of the target are still being discussed and both a windowless target and a window target were being examined. The power of the source in the MW range shows quite clearly that such technology is now ripe for development and being taken into serious consideration world-wide.

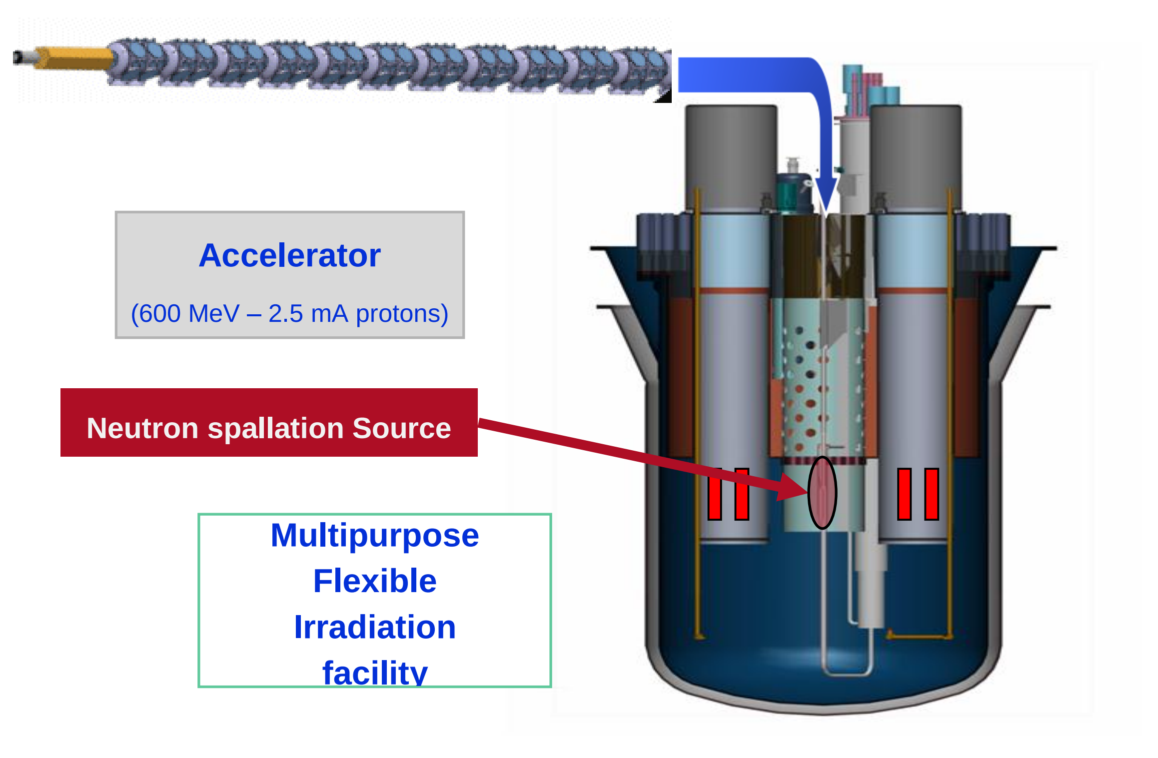

Figure 11: Projected facility MYRRHA, ref: http://myrrha.sckcen.be/

The key parameters of the MYRRHA facility are outlined in the table below, according to the area of application. They tie in quite closely with the values derived in the sections above.

Parameters	**Value**
Current	3 mA
Beam energy	600 Mev
Neutron production rate	10^{17} n/s
Application	**Requirements**
ADS demonstration	50 to 100 MWth
Transmutation studies	$F_{Fast} = \sim 10^{15}$ n/cm^{2}s,
Material research Fission	$F_{Fast} = 1$ to 5.10^{14} n/cm^{2}s in ~100 liters
Material research Fusion	$F_{Fast} = 1$ to 5.10^{14} n/cm^{2}s in ~10 liters
Fuel research	$\Phi_{tot} = 0.5$ to 1.10^{15} n/cm^{2}s
Production radio-isotopes	$F_{th} = 0.5$ to 2.10^{15} n/cm^{2}s
Si Doping	$F_{th} = 0.1$ to 1.10^{14} n/cm^{2}s

Table 4: Parameters of MYRRHA in different applications.

Ref: College of Europe, Bruges, June 10th 2010

2.2.5 ESS - A spallation source for neutron research.

The Swedish government has launched an initiative to develop a neutron research centre aimed at the biotech and nanotech sector, it has been joined by man European countries in this endeavour. The focus of the project is therefore different to that of MYRRHA which is more generalist and has a greater nuclear component, through the ADS and research on fuel and transmutation.

Currents efforts at ESS are concentrated on the development of a solid target which consists in a porous wheel cooled by helium. The target itself is a multitude of tungsten rods that are held in place between two manifold distributing cooling medium. The helium enters and leaves the wheel via the axle which is designed to be adequately Helium leak-tight by an appropriate design of the labyrinth seal By spinning the wheel at high speed and ensuring sufficient cooling the team are confident they can cope with the 5 MW beam power.

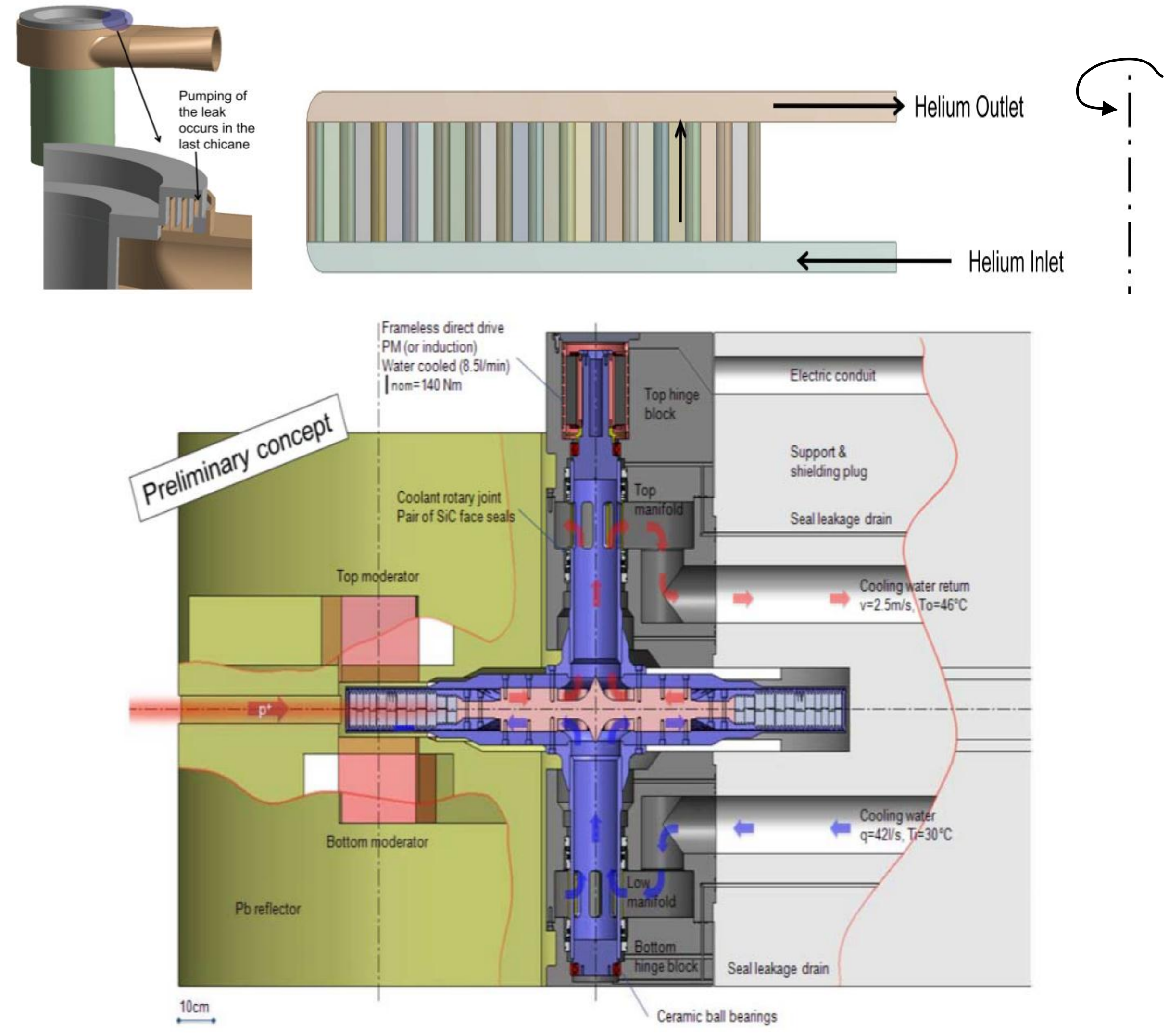

Figure 12: ESS spinning wheel design.

Ref: http://ess-scandinavia.eu/

The main challenge identified by the team relates to the leak-tightness of the labyrinth seal on the axle which constitutes quite a challenge given that Helium is one of the gases with the smallest dimensions that is frequently used to assess leak-tightness as it can get through the smallest cracks.

Should leak tightness not be adequate, this would result in gaseous contamination being spread throughout the target station since the target contains tungsten. This target metal when impacted by the proton beam at high temperature exudes a significant amount of active gases, some of them impossible to bind chemically as they belong to the noble gas species

Another challenge which will need to be examined in this project is the beam window separating the beam tube (total vacuum) from the target spinning in its target station which is surrounded by Helium. Although it is not insurmountable, the design of the beam window does pose a significant challenge as the beam will already be focused when it exits the beam tube and enters the target (see concept in figure above).

2.2.6 ISIS follow-on project at the Rutherford Appleton Laboratory

The ISIS facility has undergone continuous improvements over the past years with the recent inauguration of a second target. The STFC Rutherford Appleton Laboratory, in Chilton, Oxfordshire, has initiated in 2011 a new programme aimed at developing high-power targets in the MW range.

They have focused their attention on a concept featuring a stack of pebbles, 1 mm in diameter piled into a horizontal container, which is flushed with Helium at 10 Bar pressure. The temperatures are well below melting point and the speed remains subsonic to cool the pebbles adequately, also the pressure drop required to drive the Helium is achievable with conventional helium pumps. Compared to the ESS concept, this target offers the significant advantage of getting rid of the complex labyrinth seal; hence there is no sealing break in the helium loop used to cool the target. This should help significantly with the safety case.

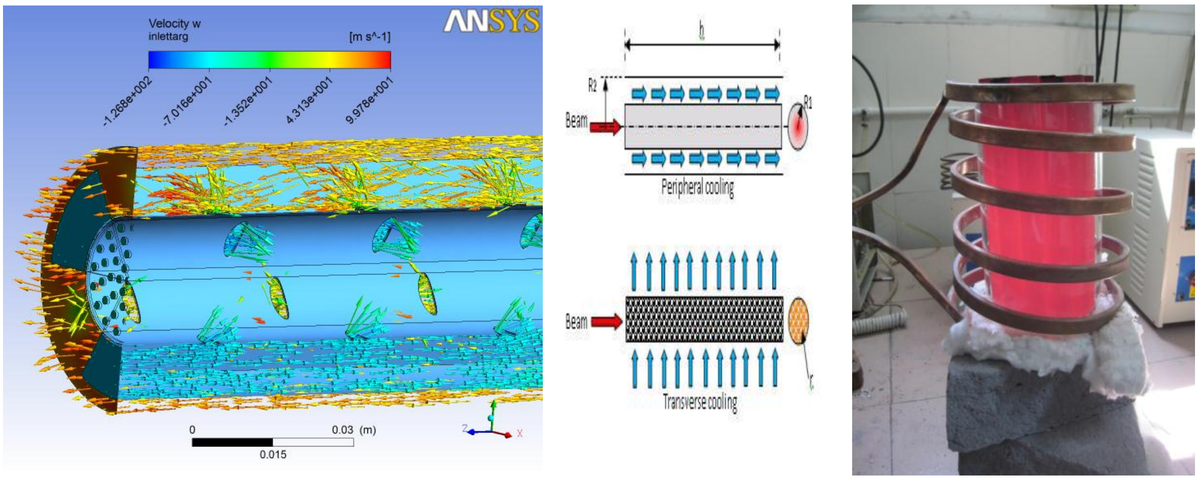

Figure 13: ISIS follow on project. He flow (left) principle (centre) testing (right).

Ref: T. Davenne

Testing of such an assembly has been attempted using a proof-of-principle geometry and induction heating to replicate the beam power deposition (see right side of figure above) The work on induction heating is commendable as until now no similar method of testing targets ahead of proton beam irradiation had been attempted.

Another of the Appleton-Rutherford team's concerns is the durability of the beam window. Inevitably the beam has to leave the evacuated beam tube and enter the helium-filled space which surrounds the target. The approach taken by Rutherford Appleton is to aim to cool the window using conventional means and aim for the highest possible density of power in the beam. Therefore, the final design may well be driven not by the resistance to heat of the pebble stack but by the capacity of the beam window to endure thermal stresses.

The performances of the target they hope to achieve are thus:

- 4MW proton beam at 14GeV
- 20mm diameter packed bed of 1mm diameter

The cooling requirements would be:

- Inlet He pressure = 11.7bar,
- outlet pressure = 10bar
- Inlet density = 2kg/m3
- Maximum Helium velocity = 497m/s

3 Target testing facility specifications

3.1 Strategy pursued in fulfilling overall requirements

One could argue that a testing facility for a 5 MW target should seek to reproduce all aspects of operational use at full-scale, in which case a facility on the scale of MYRRHA or ESS would have to be built. This is clearly not an effective use of resources as these two projects are quite sufficient to address research needs in Europe. Rather, collaborations and complementarities should be sought with large-scale facilities, either projected such MYRRHA and ESS, or already established such as SINQ at PSI or the LEP at CERN.

In order to proceed in a cost-efficient manner, the different aspects of target testing have been broken down into dedicated tasks to avoid replicating large facilities or placing such high demands on the proposed facilities, which would make the project unaffordable. Each task can be assigned to a specific facility, where it exists adaptations are made; otherwise a dedicated facility has to be built. By focusing on a particular task, it is far more likely that an existing facility may accommodate the specific testing needs, failing which the purpose-built facility which has to be built will focus on a narrower set of objectives and thus be cheaper.

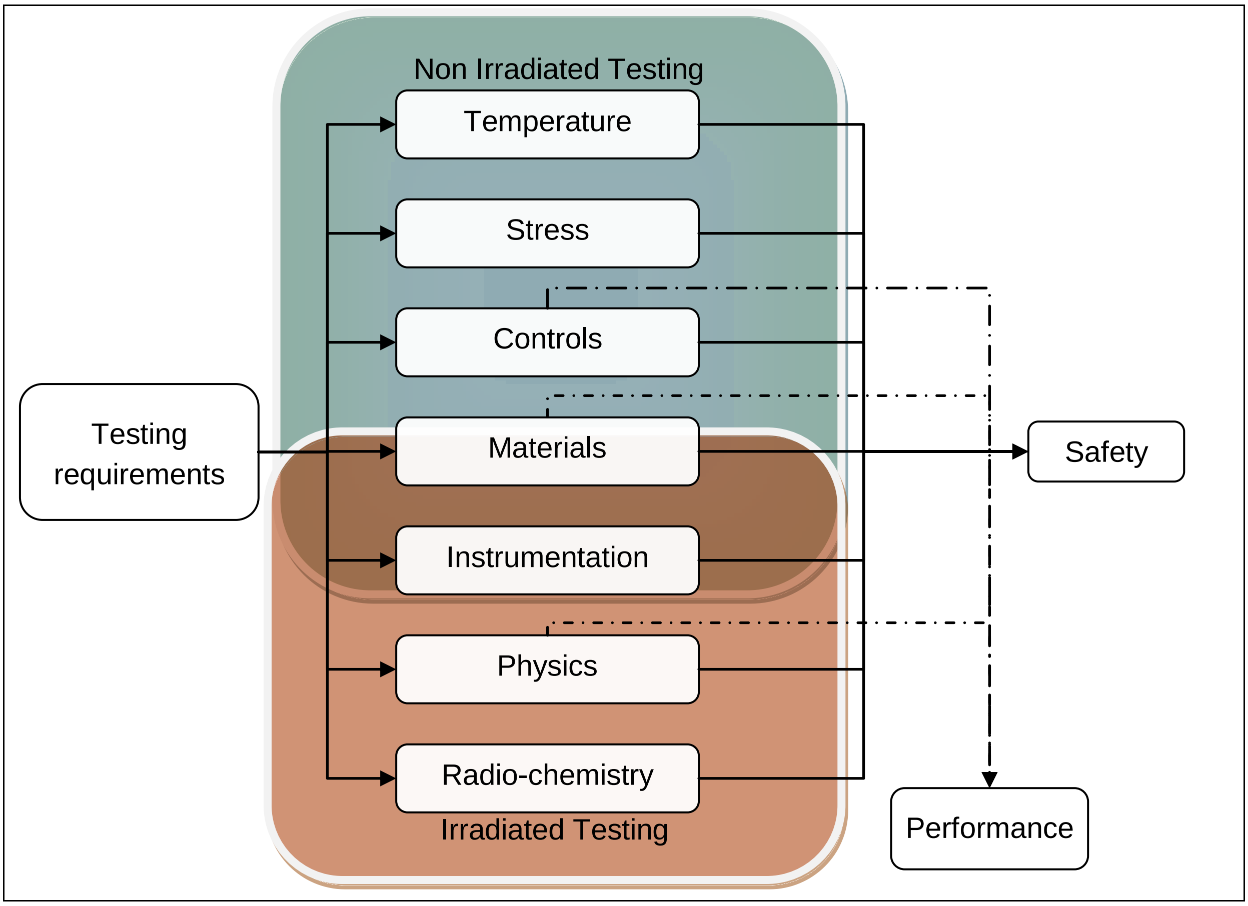

Figure 14: Multi-tiered approach to target testing.

The following sub-sections 3.1.1 to 3.1.3 examine the types of targets that are most likely to be developed and thus to need testing facilities. Thus a credible ***specification for target testing*** may be defined in sections 3.2 to 3.6.

3.1.1 Required technological breakthroughs

The breakthroughs required to make an accelerator-based technology viable are many. The most pressing surrounds the question of the density of the neutron flux and the efficiency in its utilisation.

To address this matter, the envisaged solution would make use of a compact neutron source surrounded by a lead blanket diffusing the exiting neutrons thus tailoring the neutron spectrum to enhance capture in the resonance region as would be required by the application envisaged.

Although the accelerator-based approach has some clear advantages, according to conventional wisdom, they were outweighed by postulated disadvantages such as most notably the low yield. This purported disadvantage is mainly the result of the lack of availability of an adequate neutron source to date.

The advantages of an accelerator-based approach can therefore be brought to bear if a novel approach is taken, based on the following new insights gained from recent experimental feedback.

- The neutron source can produce a high flux of neutrons using technological developments from recent projects (Eurisol-Megapie).
- The strength of the flux can be optimised by the geometry of the blanket and reflector surrounding the target thus boosting efficiency.
- An optimised neutron spectrum can make full use of the resonance peaks for neutron capture in the epithermal region.
- The absence of water cooling makes it easier to optimise the spectrum to suit the specific need of the application envisaged.

Hence the fundamental questions which need to be answered are:

- is a high intensity neutron source commercially viable?
- can it be made using conventional technology and operated safely and cheaply?

Given the wish-list quoted above, it would seem that two routes are possible:

- solid targets using a non-capturing gas (Helium) cooling and/or
- liquid metal targets

The current chapter explore the possibilities offered by these two alternatives and the required infrastructure needed to test them. The previous sections determined the fundamental parameters for the TIARA high-power target development which should govern the choice of test facilities laid out in the current chapter. They are contained in the table below.

Parameters	**Value**
Beam power	200 kW- 5 MW
Beam energy	70-Mev – 1 GeV
Heat deposition in target	10 kW/cm3
Source neutron production rate	up to 10^{18} n/s
Source surface neutron flux	up to 10^{15} n/cm²s
Target cooling medium	Helium / liquid metal
Target material	Be, Ta, W, Pb, Bi

Table 5: Governing parameters for the choice of testing facilities

The characteristic of the target which would be developed have been defined. The next sections will examine in detail the targets and corresponding facilities which will be needed in order to validate experimentally a target, both with and without irradiation.

3.1.2 Options for developing solid state targets

Solid state targets have been the traditional means for obtaining neutrons using the spallation process, as shown above. The cooling medium in past has been water which suffers a number of disadvantages in terms of the neutronics, tritium production, chemical or mechanical (steam explosion) interactions with the target material. For future development the team proposes to go beyond water cooling and examine the following configuration to cool solid targets:

- plates of varying thickness, suited to the local beam power deposition and arranged at right angle to the beam, cooled by high pressure high speed helium,
- pebbles stacked in a container, cooled by high pressure high speed helium,
- a spinning wheel cooled by high pressure high speed helium.
- High temperature target (2000 °C) cooled by thermal radiation exchange to an external heat sink cooled conventionally.
- Medium temperature target (500 - 1000°C) cooled by conduction cooling thru a high-conductivity medium to an external heat sink cooled conventionally.

In all instances these different options will necessitate the development of a beam window, given that the target material is surrounded by high pressure helium which the window must resist in addition to the thermal stresses. The window can be situated at a certain distance to the target and blanket, in which case the beam will travers a given amount of helium resulting in losses and activation. The studies for this window should include:

- Conventional water cooling using minimum thickness film cooling and optimal distance of the window to the target in relation to activation and beam losses in the helium traversed by the beam versus neutronics absorption in the window cooling water.

- Minimum allowable size of the beam / maximum beam power deposition of the beam for helium-cooled windows.
- High conductivity materials such as SiC / amorphous diamond cooled passively through heat sink

3.1.3 Options for developing liquid metal targets

The schematic below highlights how an improved safety-enhanced liquid metal source may be built, taking on board the combined experience from many liquid metal developments. The advantages of compactness and containment are due to the fact that the protons beam in no way penetrates through the containment structure. Also the heat exchanger is physically decoupled from the neutron source with a gap containing helium between the two serving as both a conductor of heat but also an inherent leak detector and barrier. A further advantage of the proposed design lies in the fact that it is easily scalable to different power levels by simply adapting the lengths of the heat exchanger main corpus. In addition due to its compactness it may be positioned horizontally or vertically.

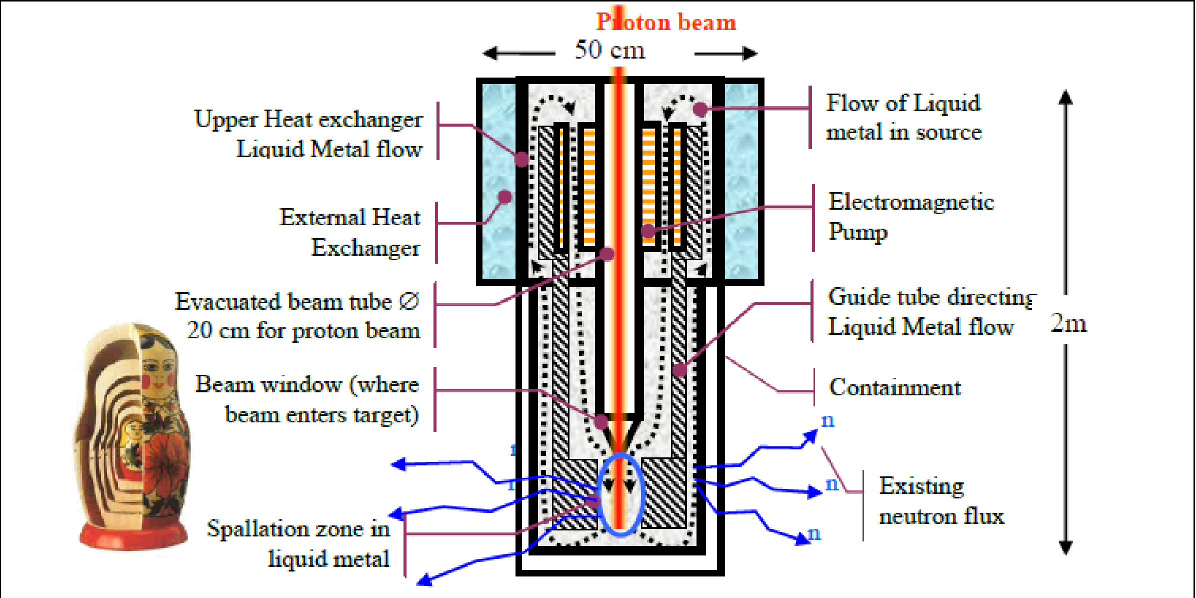

Figure 15: proposed layout of a compact liquid metal neutron source.

Ref.: K. Samec, ICAPP Nice 2011.Note: the design would also allow a solid target in the spallation zone (blue circle) cooled by heavy water, albeit at lower power levels.

3.2 Non-irradiated testing requirements

3.2.1 Solid target testing

To address the testing needs of the various target designs being examined, the focus should be on the following engineering aspects

1. It is necessary to be able to replicate helium flow conditions in the target, hence to set up a loop using gas as a coolant with the following main components:

- Gas loop 16 Bar rated tightness.
- Pumps rated at 2 kg/s (for He at 10 Bar , 5193.2 [J/kgK] , 2 [kg/m3]).
- Heat exchangers able to handle 5 MW * 70% = 3.5 MW.
- Gas flow meter.
- Dedicated multiple helium leak detectors if the wheel target design is to be tested.
- Pressure taps and Pitot tube locally.
- Thermocouples mounted in gas stream
- Data acquisition through appropriate gas-tight connectors to all sensors. Separate low-frequency multi-channel acquisition from fast acquisition on a few selected channels.
- Control and power.
- Adequate data storage.

2. In order to replicate the beam it is necessary to produce an environment that is realistic in terms of heating. Different heating methods are to be used:

- Volume heating: induction for the solid target replication deposition from the beam sufficient to reach 3.5 MW (5 MW @ 70% deposited beam fraction)
- Surface heating Laser rated at 10 kW to test the window or any other point of entry of the beam, depending on the configuration chosen (wheel).
- As a backup to the induction method, conventional Ohmic resistors may be used. They lack the power density required for the full beam but may be used however for smaller sub-scale testing. Power limit ~200 [kW]

3. In order to assess the effect on the target, it shall be adequately instrumented:

- Thermal and mechanical stresses: strain gauges of different types. The majority should withstand up to 300°C and may be based on gratings deposited on conventional thermoplastic. A few will be needed to withstand up to 1000°C and can rely on interferometry/fibreglass strain gauge technology
- Thermocouples on structure.
- Infrared camera to capture thermal maps, it is a method that is particularly well adapted to a Helium environment which is transparent to IR
- Low acquisition rates are sufficient for structural response.

Irradiated testing is the subject of a dedicated section further on in the current report and is common to both types of targets, liquid and solid.

3.2.2 Liquid target testing

Testing liquid metal sources require setting up a liquid metal loop with all measurement devices required for measuring pressure, temperature flow and local velocities where needs. Prior experience gained in this respect indicates that selecting specific components for dedicated tests such as the beam window is a proven way forward. In a graded approach aimed at minimising risk, integral testing is required only once the component testing is successful.

Component testing is of particular relevance to liquid metal targets as the coolant used in the target is unfamiliar. Hence a graded approach is recommended, breaking down the overall task into distinct phases which focus on particular aspects of thermo-hydraulics, thermo-mechanics, coupling fluid/structure etc. For this reason it is necessary first to construct a smaller liquid metal loop where given components may be tested. As such the liquid metal development includes also the development of components which cannot be bought off-the-shelf

1. Sub-scale loop for component development and testing, fundamental thermal-hydraulics physics investigation:

- Liquid metal loop 16 bar rated tightness.
- Pumps rated at 1 l/s (for LBE at 10 [kg/m3]).
- Heat exchangers able to handle 100 kW.
- Flow meter. .
- Pressure taps and Pitot tube locally.
- Thermocouples mounted in LM stream
- Data acquisition through appropriate gas-tight connectors to all sensors. Separate low-frequency multi-channel acquisition from fast acquisition on a few selected channels. (may be common with solid target development)
- Control and power.
- Adequate data storage.

It should be noted that the loop will be developed with its essential components such as the pump, the heat exchanger and the flow meter. Existing expertise may be called up in private industry and research labs to accelerate their development but they are in no way standard components. These dedicated tasks need to be planned and contingency measures set in advance to avoid any critical paths.

Once the sub-scale facility is operating, dedicated tests for evaluating physical phenomenon such as cavitation, fluid-structure interaction or technological test such as sensor development may be envisaged.

2. Full-scale loop for target development and testing:

- liquid metal loop 16 Bar rated tightness.
- Pumps rated at 15 l/s (for LBE at 10 [kg/m3]).
- Heat exchangers able to handle 3.5 MW. (ultimate heat sink to be shared with solid target development)
- Flow meter.
- Pressure taps and Pitot tube locally.
- Thermocouples mounted in LM stream
- Data acquisition through appropriate gas-tight connectors to all sensors. Separate low-frequency multi-channel acquisition from fast acquisition on a few selected channels. (may be common to previous task)
- Control and power.
- Adequate data storage. (TB)

The components used in the full-scale loop will be scaled-up from the sub-scale loop and should be developed successively, effectively eliminating any development risk.

3. In order to replicate the beam it is necessary to produce an environment that is realistic in terms of heating. Different heating methods are to be used:

- Volume heating: induction for the solid target replication deposition from the beam sufficient to reach 3.5 MW . First a sub-scale test will be necessary to ensure the high-frequency electromagnetic waves do not affect the flow properties.
- Surface heating Laser rated at 10 kW to test the window
- As a backup to the induction method, conventional Ohmic resistors may be used. They lack the power density required for the beam and may be used however for smaller sub-scale testing. Power limit ~200 [kW]
-

4. In order to assess the effect on the target, it shall be adequately instrumented; some of this instrumentation may need further development due to the particular environmental challenges posed by liquid metal. The sub-scale testing facility will be used in providing the correct representative operational environment for these developments.

- Thermal and mechanical stresses: strain gauges of different types will be used, some existing, some needing development and/or validation. The majority of gauges should withstand up to 300°C and may be based on gratings deposited on conventional thermoplastic. A few will be needed to withstand up to 600°C and can rely on interferometry/fibreglass strain gauge technology.
- A technology for picking up stresses on liquid-metal environment will need to be developed from previous experience in the MEGAPIE full-scale leak test for which this technology was developed including connectors, Furthermore it will be necessary

to distinguish mechanical from thermal stresses using strain gauges as thermocouples may prove unreliable due to the thermal conductivity of liquid metal which disturbs their proper functioning quite strongly

- Thermocouples on structure. It will be necessary to calibrate the effect of liquid-metal and elaborate strategies for distinguishing more effectively liquid metal temperatures from structural temperatures.
- Infrared camera to capture thermal maps on all external surfaces. The method developed by J. Patorski for measuring the heat transfer coefficient on liquid-metal wetted surfaces in Megapie should be implemented and further developed for greater flexibility and ease-of-use.
- Low acquisition rates are sufficient for structural response.

The testing of liquid-metal targets under irradiation is the subject of a dedicated section in the following.

3.3 Safety testing

The safety case rests on multiple containments which must be engineered to resist multiple failures happening consecutively or simultaneously depending on credible hazard assumptions. As recent events in Fukushima have demonstrated defence in depth is required at all levels to ensure robustness in the face of extreme events. In the context of TIARA, different innovative target concepts will be studied. It therefore makes sense, to study hazard assumptions before embarking on a safety test of the target.

3.3.1 Hazard assumptions

The hazard assumptions may be derived from the recommendations of the Western European Nuclear Regulators' Association (WENRA) concerning the safety of nuclear power plants. The hazards listed in the document entitled “Reactor Harmonization Working Group, Harmonization of Reactor Safety in WENRA Countries Report, Annex 1 Issues E & F” from 2006 are adapted to the particular requirements of a neutron source in the table below.

Amongst the hazards listed in the table, some involve the full-scale testing of the source, other require sub-scale testing to ensure physical aspects are fully covered which underlie the system performance. The following sections will list those aspects needing particular attention

Section [1]	Relevant Safety Case
Annex F / §5.1	(...) The following types of PIEs shall, be included: • Forced decrease of reactor coolant flow; • Inadvertent opening of pressuriser valves • Inadvertent opening of safety valves; • Heat exchanger tube rupture • Loss of off-site power • Loss of core cooling
Annex F / §5.3	(..) The following types of external events shall be included in the safety analysis: • Extreme wind loading; • Extreme outside temperatures, icing; • Extreme rainfall and site flooding; • Earthquake; • Aircraft crash;
Annex F / §5.4	(..) Beyond design basis events shall be considered: • Station blackout; • Total loss of feed water; • LOCA together with the complete loss of one emergency core cooling system; • Loss of ultimate heat sink; • Multiple heat exchanger tube ruptures • Coolant line break together with a heat exchanger tube rupture.

Table 6: Governing parameters for the choice of testing facilities.

Ref. : K. Samec, ICAPP 2011 conference proceedings

3.3.2 Sub-scale and component testing

The following aspects needing further detail study on a subscale level have been derived from the table above,

1. Annex F / §5.1: safety valve opening

In most targets the safety valves consist in simple bursting disks which are rated to break open at a given pressure. This results in a containment being breached and remaining open. In NPPs it is common to have spring-loaded safety valves which open and close. In this way only the pressure spike is released, but once pressure has been decreased the valve closes and containment is re-established. This is an important mitigation strategy to prevent high doses of being released. It would be recommended to study how such a technology could be adapted to both liquid-metal and solid targets.

2. Annex F / §5.1: Heat exchanger tube rupture

The heat exchangers in both the solid target and liquid metal target are new developments. They contain fluids which can interact. There are some well-known examples such as the injection of water in LBE which causes a steam explosion. Likewise sodium and water leads to fire. The ingress of Helium contaminated by polonium in a water cooling circuit would lead to its contamination. Depending on the type of target option and heat exchanger configuration that is retained, it is necessary to study the interaction of the primary fluid (in the target) with the secondary fluid (extracting heat out of the target) from the point of view of: physical interactions such as; pressure, species transport and diffusion,

3. Annex F / §5.3: Earthquake

The source is most likely to be a compact object cylindrical in length held horizontally or vertically at one end. Strategies to mitigate the effects of earthquake should not focus solely on the containment of the target station, but also on all possible source of contamination, the most prominent being the source. In line with the current practice of earthquake-proofing all major primary components inside the NPPS, it is equally necessary to ensure structural margins on the source and its connection against earthquake. This may be reached by isolating the source with adequate absorption elements and ensuring movements of the connecting pipes and cabling are within tolerable limits. Provision should be made for testing a source mock-up representative in mass and inertia on a shaker table using the latest earthquake assumptions valid in Switzerland extracted from the 200/ PEGASOS study published by the Swiss nuclear regulators ENSI.

4. Annex F / §5.4: Multiple heat exchanger tube ruptures

The design of the heat exchanger should ensure that no contamination is released into the environment in the event of rupture on the primary or secondary side. Demonstrating this goal in a dedicated test focusing only on the heat exchanger is mandatory. The heat exchanger shall be placed on a dedicated test bed where ruptures shall be artificially provoked on each side in succession and then on both side simultaneously. The size of the leak shall be derived using analytical tools to cover the worst case scenario.

3.3.3 Full-scale test of the entire target

Full-scale testing is essential to many of the cases listed in the WENRA hazard assumption above. Assuming a prototype is available the test may be carried out in an appropriate test cell. In effect, this type of testing concludes the development of the prototype and should validate the concept. The establishment of dedicated facilities is therefore a low priority in the initial stages of the project which needs above all the sub-scale testing mentioned in the previous paragraph during the first 80% of the projects development period.

The test will be grouped into categories, as many of the hazard assumptions may be covered in the same test facility. Three categories have been distinguished. The first concerns the hydraulics. The second category concerns the mechanical test. Finally the third category concerns the leak test in which all fluids are assumed to leak out into the containment. The safety cases extracted from the WENRA table are treated as follows in the individual test cells.

1. Hydraulic test cell:

Hazards relating to hydraulics in the target to be replicated in a full-scale test of the target:

Annex F / §5.1	Forced decrease of target coolant flow;
	Loss of off-site power
	Loss of target cooling
Annex F / §5.4	Station blackout;
	Total loss of feed water;
	Loss of ultimate heat sink;

The test cell shall allow the target to be connected to an external heat sink and heated by the methods specified above. Appropriate placement of valves and controls will seek to replicate accidental conditions.

2. Mechanical tests:

Hazards relating to hydraulics in the target to be replicated in a full-scale test of the target:

Annex F / §5.3	Extreme outside temperatures,
	Earthquake;
	Vertical fall

The test facility will focus primarily on puncture tests at critical locations as well as dynamic solicitations. It is worth pointing out that for some of the larger scale testing; it may be advantageous to seek an industrial contractor in order to lower costs. An example of a large scale facility that is available for defined periods from an industrial partnership is illustrated in the figure below. The scale is sufficient in terms of dimensions to accommodate reactor-sized component 5 metres in diameter and heat them to a temperature of 300°C. The size of most target concepts would easily fit in such a facility and the fact that the neutron source is in itself a distinct component makes it quite suited to transport.

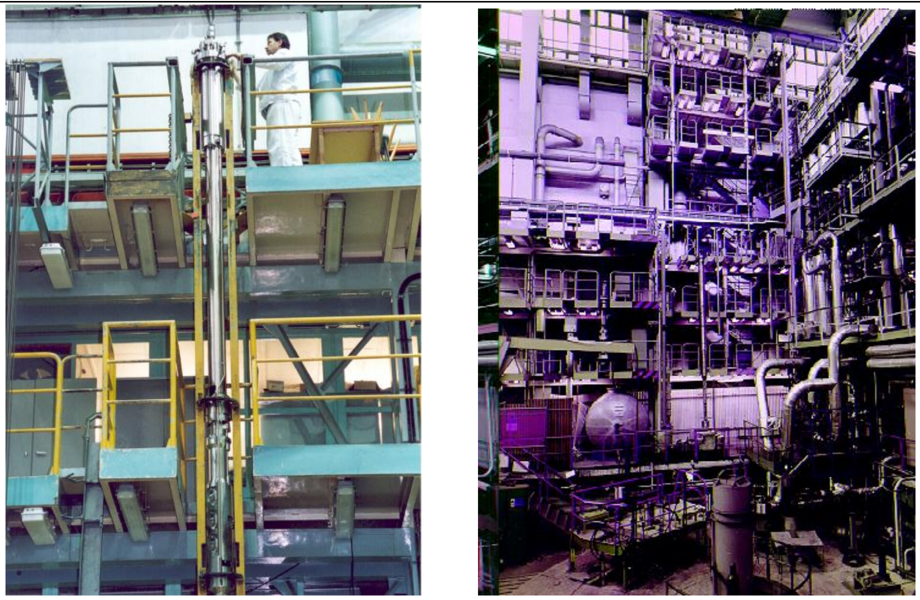

Figure 16: Thermal hydraulic test facility available at ŠKODA Jaderné Strojírenství

3. Leak test:

Hazards relating to hydraulics in the target to be replicated in a full-scale test of the target:

Annex F / §5.4 Coolant line break together with a heat exchanger tube rupture.

The MEGAPIE target was tested in an all-encompassing full-scale leak test in which the liquid metal inside the target was pressurised to 10 Bar an released into the containment. Temperatures and stresses were then measured. A similar test facility as the one used in MEGAPIE, shown below, should be used and experience can be drawn from this project.

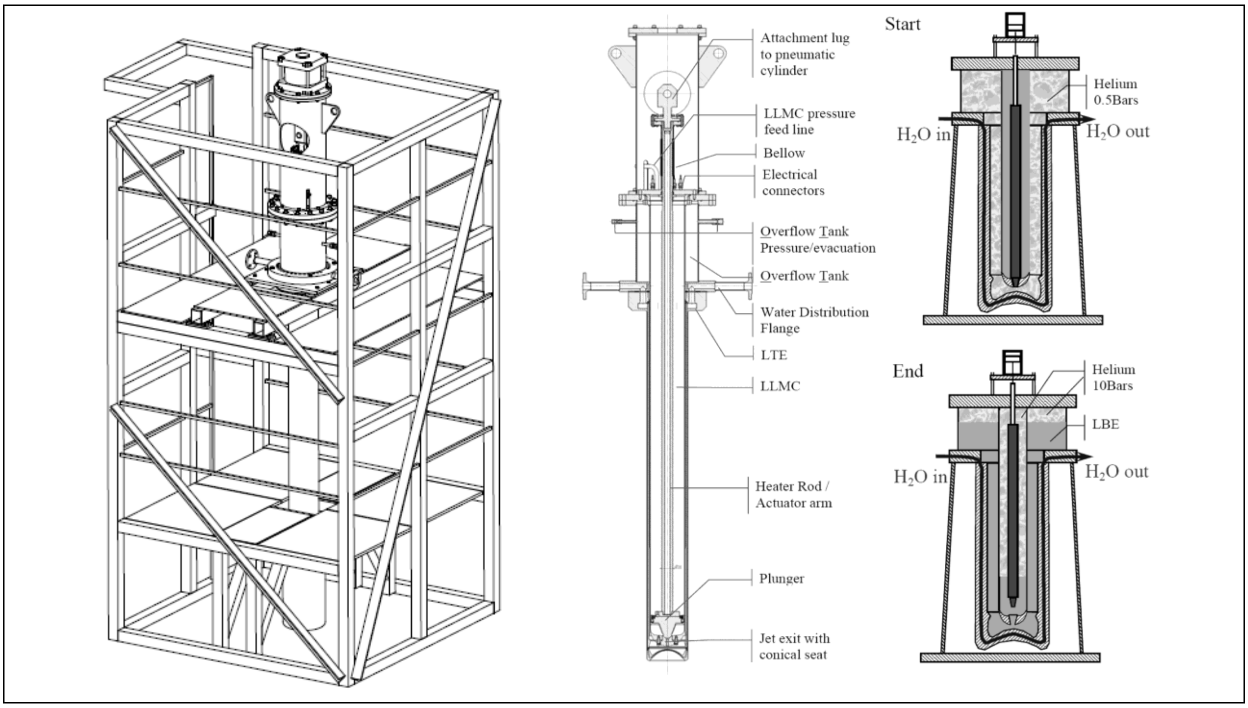

Figure 17: Test stand (left) Test object (centre) Principle (right) Megapie Leak Test

Ref.: K. Samec, ANS Nuclear Technology 2008

3.4 Irradiation testing

Previous requirements focused on the thermal, hydraulic mechanical and systems integration/safety aspects of testing the neutron source. Essentially, the facilities outlined in the previous sections should replicate all the conditions that the neutron source is likely to encounter when it undergoes irradiation. There remains however one important caveat, that is the effect of irradiation on the source in terms of:

- Radio-protection
- Neutronics / isotopic efficiency
- Material and instrumentation degradation
- chemical aspects

The simplest way of assessing the first two subjects would be to carry out irradiation testing of the source under proton irradiation at existing facilities. This type of test can then be usefully complemented by investigating separately the effect of irradiation on the target structural materials and instrumentation (see chapter 3.5) as well as the effect on the chemistry of fluids inside the target (chapter 3.6). The current chapter will focus only on irradiation testing of the target system as a whole at partial or full-scale for the first two objectives.

Irradiation facilities are expensive a factor of 10 is usually applied to the cost of all equipment operating under such conditions and it therefore makes sense to first examine whether use could be made of existing facilities. In order to test a target under irradiation, a flexible solution has to be found if existing facilities are to be used to full effect as many such facilities in the world have a tight schedule and require a quick turn-around from experimenters. As long as the target to be tested is compact and may be transported easily, then testing at various facilities may be envisaged. It may then be possible to put a newly developed spallation target that has passed all non-irradiated tests, in an irradiation test using facilities that are available and have the required flexibility. Given large facilities have tight schedules, the possibility of using them may prove more difficult yet achievable if the proper organisational procedures are put in place.

An example of a user-friendly facility potentially suited to irradiation testing is the HiRadMat facility at CERN, shown below and currently being commissioned. The facility will be examined in the following as an example of the type of collaboration which may be pursued in the field of irradiation testing.

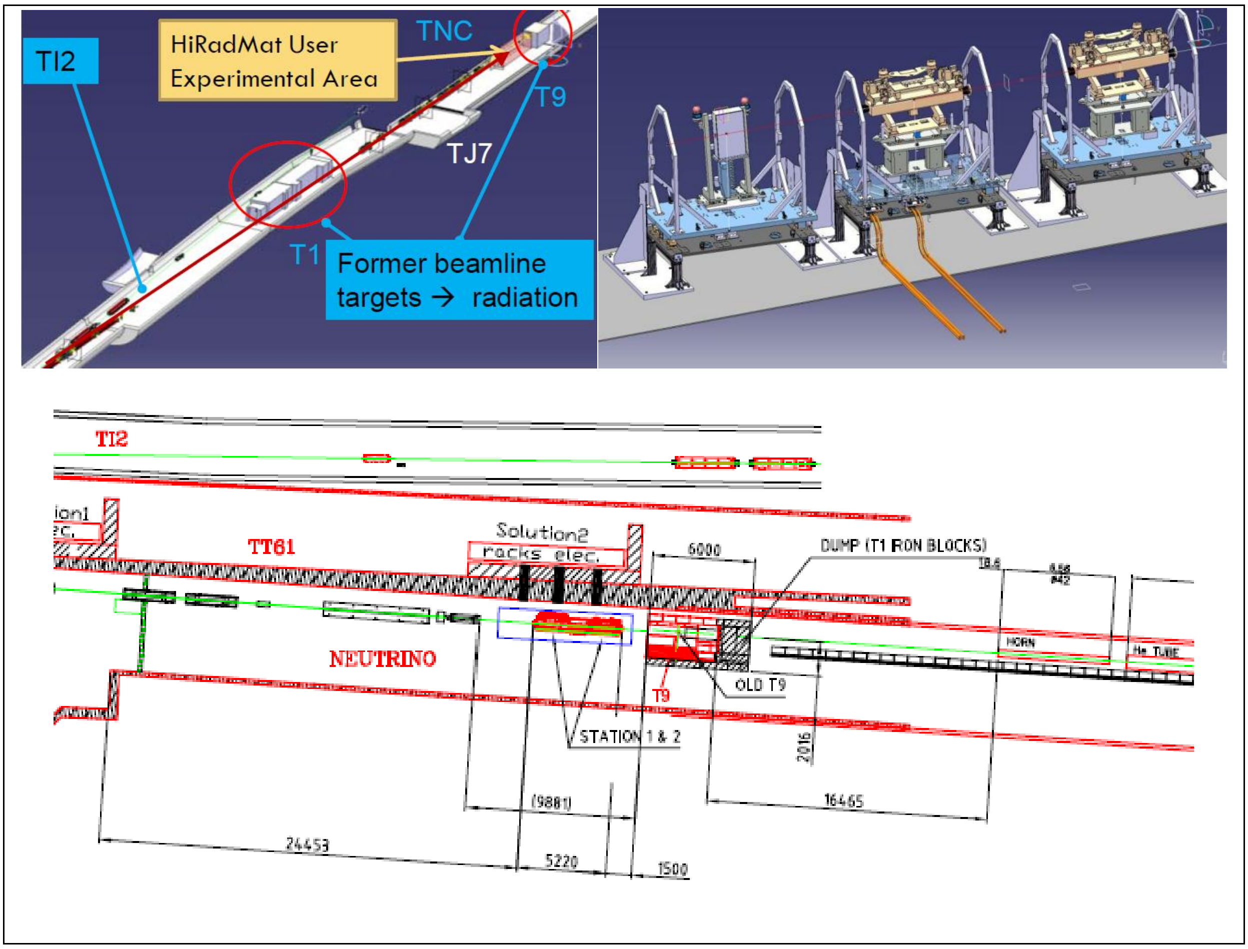

Figure 18: HiRadMat Irradiation testing facility at CERN available from 2012

Ref.: http://cern.ch/hiradmat

It should be emphasized however that HiRadMat is used purely as an example, and many other valuable collaborations may be sought such as for instance:

- SINQ at PSI which has extensive experience form the Megapie project
- ISIS at Appleton Rutherford (UK) which already has two targets working in parallel.
- SNS at ORNL (US) with one operational target and a second one planned.
- JSNS at J-PARC (JP) with a facility currently under temporary shutdown.
- The 30 MeV cyclotron at ŘEŽ Ústav jaderné fyziky in the Czech republic
- High power facilities which exist such as JINR-Dubna in Russia and where energies up to 2 GeV and several mA may be reached.
- Future facilities being built may also be envisaged as locations for testing new target concepts. ESS or MYRRHA would be prime candidates.

The key dimensions of the testing area in HiRadMat are given in the table below. The volume is of particular interest as it has to be larger than most current target designs, this is the case; both liquid and solid metal targets occupy no more than 20 litres as far as the irradiated part is concerned. Also the weight supported in the test gantry is well below that of Megapie, the largest target to date and dimensions are sufficient if the larger targets such as Eurisol / Megapie are inserted horizontally and also tested in this position.

Parameter	**Value**
Volume of exposed material	≤ 16.8 litres
Equipment size	
Length (flange-to-flange)	≤ 7.0 m
Width	≤ 1.0 m
Height below beam line	1.1 m
Heightabove beam line	≤ 0.8 m
Weight	≤ 4,000 kg
Handling zone (L ×W ×H)	15 ×2.0 ×2.2 m3

Table 7: Accommodation of target specimens in current testing facility HiRadMat

The parameters of the beam are given in the table below. The beam is not continuous but pulsed. In light of the fact that irradiation testing is carried out for assessing radio-protection needs and neutronics performance, pulsed operation actually brings some benefits as the measurement of the neutron spectrum and gamma spectrum can be made with sufficient accuracy due to the higher statistics over a shorter period of time . The short pulse mode has the benefit of decreasing the radio-toxic inventory needing cool-down after irradiation testing. As long as the target installed inside the irradiation facility is fully representative of the materials used in the operational target, measurement of the physics parameters necessary for radio-protection assessment and neutronic or isotopic performance predictions will be essentially correct.

In terms of heating and stress the instant heat deposition is of course quite considerable, 5 orders of magnitude higher that the continuous heat deposition the target would encounter in operation. However the duration of the pulse is short; only 7.2 μs and thus thermal inertia can be counted upon to mitigate the temperature peaks and gradients as well as the thermal stresses. This aspect of testing the target would of course be checked using Computational

Fluid Dynamics coupled with Finite Element programs for final checking of the stresses and temperature during testing under irradiation.

Unit	Value(proton beam)		Value(lead ion beam)
Beam energy	GeV	450	36.9×103(177.4GeV/n)
Pulse energy	MJ	2.4	28×10-3
Pulse length	Ms	7.2	7.2
Peak power	GW	340	2.3
Normalized emittance(1σ)	Mm	3.5	1.4
σx×σy at exp.(baseline)	mm2	1.0	1.0
σx×σy at exp.(request)	mm2	**0.25–4.0**	0.25–4.0

Table 8: Beam in HiRadMat

It is apparent from the energy of the beam and its narrow focus that it would not be ideally suited to typical spallation targets of the type needed in the context of the current work. The facility could however be adapted in this respect. The key parameter which needs to be changed is the beam energy of 450 GeV, an energy which leads to a deposition length of several meters, well beyond what is to be expected for normal neutron spallation targets. However this drawback can be turned into an advantage if a method can be found to lower the energy so as to vary the incoming proton energy at will whilst increasing the current, either by scattering the incoming 450 GeV proton beam on an intermediary target to boost and scatter forward the incoming protons, or electromagnetically stripping of an electrically charged hydrogen gas.

A further aspect of radio-protection which would not be covered by the present type of irradiation concerns the long-term effect of irradiation. Such effects are two-fold. On the one hand irradiation will produce new elements in the target, so-called transmutation. In the target material itself be it liquid or solid the radio-toxic inventory thus accumulated needs to be assessed, and categorised into solid, fluid and gaseous products. This works concerns primarily radio-chemists and can be carried out on small samples placed under long-term irradiation (refer to chapter 3.5 below)

Another long-term effect of irradiation is the embrittlement of structural materials. This topic has already been researched extensively in Megapie and it is suggested that by using the same materials as in that project, research in materials can be kept to a minimum. It may however serve lon-term goals to promote this type of research although it is not critical to the current task due to prior experience.

3.5 Radio-chemical analysis

Some additional testing facilities are needed that do not directly relate to the target development itself but are still closely connected to its safe operation. These will be mentioned briefly for completion and it is strongly suggested they be treated as additional work packages in a more detailed study of the proposed facility for high-power targets.

First and foremost in the complementary testing facilities needed, radiochemistry is a branch of nuclear technology which is of essential importance to radio-protection. Such an investigation is particularly relevant to high-power neutron sources where much of the spallation products are present in the form of gases. Gases present a risk of inhalation which can contribute greatly to doses rates.

From a radio chemist’s point of view, it is necessary to establish the scale and source of possible radio toxicity in the neutron converter. These studies could focus on:

- Evaporation studies of radio-toxicity sources
- Permeability and diffusion: investigation of the effectiveness of barriers
- Calculation using CFD to replicate simplified experimental setups and validate numerical methods used in calculating dose rates from source terms.
- Chemical biding: once identified, how may the waste be contained and treated?

Sub-scale testing on small sample irradiated over a long period of times has proven effective in Eurisol to establish the best methods for dealing with these matters in principle at a relatively modest cost. Typical installations and project costs ranged in the 100 k€, provided the irradiation of the sample is provided free of charge in the context of collaborations with the same institutes as mentioned in the previous section.

3.6 Options for improving the material technology base

It should be stressed that the current work package should refrain from using any materials whose properties are unknown in areas critical to safety. Rather the emphasis should be on established materials which have proven their reliability in previous experience. The same can be said of instrumentation which has in the past relied primarily on proven technologies such as thermo-couples and pressure transducers.

Given this constraint, materials science may be called upon to make a contribution to target development although it is not expressly mentioned in the work package covered by TIARA. Should this option be pursued it should be planned as a separate task necessitating a dedicated budget to avoid budgetary overlaps as material science in irradiated conditions is notoriously expensive. Furthermore the existing range of materials is adequate to launch a target development program without further material investigations, provided proper engineering practices and precautions are in place. The ideas outlined below are therefore purely speculative at this point.

As an indication of the contribution material science could make, a short summary is presented of possible tasks. There is a wealth of information available for conventional material irradiated below 2 [dpa] that has been extensively documented by the CEA for instance; the data is complete, consistent, statistically sound and therefore useable by engineers. The situation for highly irradiated materials is far patchier; mostly disparate sets of experimental data are available but at vastly different conditions of irradiation time, temperature, loading conditions, corrosive environment, etc.

In a properly organised systematic approach to validating materials under conditions of high irradiation, it would be useful to focus on a few parameters that are critical to engineering progress but organise them in a systematic manner with adequate statistical evaluation rather than one-off values.

The values that are of primary importance are as follows:

- Young's elasticity modulus [N/mm^2]
- Thermal expansion coefficient [% / K]
- Elastic limit [N/mm^2] (where relevant tension/compression otherwise tension)
- Yield strength [N/mm^2] (where relevant tension/compression otherwise tension)
- Yield elongation [%]
- Stress intensity factor [N/mm$^{3/2}$]

These values should be determined experimentally and based on a sufficiently large representative sample base allowing a statistical evaluation to be made so as to deliver mean values within a given confidence interval.

The conditions under which the materials should be tested would focus on two primary parameters:

- Irradiations dose [dpa]: from 2 to 20 dpa
- Temperature [K]: from 20°C to 600°C for structural materials
  From 20°C to 2000°C for target materials

In addition, effects such as corrosion and other pertinent environmental conditions should be taken into account if relevant. For instance, for stainless steel in contact with LBE, care should be taken to reproduce the actual conditions with regards to oxygen content, surface preparation, LBE flow conditions…

Provided an equivalent number of dpas is reached, the effects of radiation can be produced using protons electrons or neutrons, although the latter case may be more difficult. It is possible to use small installations by concentrating a beam on a relatively small sample. For instance an electron accelerator using beam control can sweep a sample two dimensionally and thereby produce a sufficiently large irradiation dose over a larger sample.

4 Conclusions

The report has specified the essential needs for a high-power target station development based on the latest developments in this field. An attempt has been made to not pre-empt the choice that will be made by the designers of the target in the definition of the needs, but rather to open the field of possible collaborations in order to give target designers of the future the widest possible choices.

The possibility of developing liquid metal (LM) target has been frequently mentioned as a viable option for high-power targets, without excluding solid target development which is evolving currently as well in the quest for ever higher power densities. The attractions of LM in technical terms must be set against the increase in overall specification demands which are most likely to lead to a cost increase over a purely solid target development program.

Ideally both solid and liquid metal targets should be developed in parallel so as to promote dissemination of knowledge. Some of the facilities may be shared between a solid target testing station and a liquid metal target testing station if both options are pursued. .However it is quite clear that a major upgrade of the necessary testing facilities will be needed if liquid metal is to be considered seriously as an option.

Therefore a priority should be set to examine the different target options outlined in the introductory part of this report and carry out a rough trade-off study to ensure the merits of liquid-metal technology are worth the additional investment their development will require. First and foremost the limitations imposed on the beam size and power if a solid target were to be selected must be compared against foreseeable demands, to check whether the current and foreseeable solid target development technology may be reaching its limits –or not.

Only then will it be possible from a project management point of view to direct further development of the targets testing station in a cost-efficient manner consistent with prioritising resource allocation to areas most likely to enhance significantly the technology base.