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TRL analysis of IFMIF-DONES

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ABTRACT

This work presents an analysis of the IFMIF-DONES design maturity and the necessary activities to increase it up to the level required to launch the procurement phase. The analysis has been performed using a Technology Readiness Level (TRL) methodology. The TRL scale and definitions employed in EU Horizon programs have been found to be appropriate for this assessment, with some modifications to consider the IFMIF-DONES peculiarities.

The level of Technology Readiness needed for launching the procurement of each subsystem or component ("target TRL") has been established. From the comparison between the present TRL and the target TRL, the elements requiring further development and validation have been identified and the experimental activities needed to increase their maturity have been defined.

The results of the TRL assessment for the accelerator, lithium and test systems of the facility are presented together with a brief outline of the most relevant validation needs identified.

1. Introduction

IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Early Neutron source) [1,2] is a high flux neutron source generated by the interaction of a high current (125 mA) deuteron beam accelerated to 40 MeV, and a liquid lithium target. The installation forms part of the EUROfusion Roadmap strategy [3], being its main objective to qualify DEMO structural materials.

The facility comprises five groups of systems: the Accelerator Systems, based on a linac, that produces the beam with the required shape and characteristics; the Lithium Systems, responsible for generating the stable liquid lithium jet exposed to the deuteron beam; the Test Systems, that comprise the test cell where the neutron source is generated and the test modules to be irradiated; the Central Instrumentation and Control Systems, responsible for overall plant control; and the Site, Building and Plant Systems, that include the buildings and service systems providing power, cooling, ventilation, remote handling of components among others. The facility is organized according to a Plant Breakdown Structure, where each group of systems is subdivided in a number of subsystems and components.

An evaluation of the present maturity of the IFMIF-DONES design has been performed with the aim of detecting those subsystems and components that require additional research and development to attain a well-established and thoroughly tested design before initiating their procurement process.

This analysis has been developed using a methodology known as Technology Readiness Assessment (TRA) [4,5]. Following this methodology, the elements of the project to be analysed are the so-called

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Critical Technology Elements (CTEs). These are defined as at-risk technologies essential to the successful operation of the facility, which are either new or applied in innovative ways or under a different environment. After the analysis a Technological Readiness Level (TRL) is assigned to each CTE, according to a given TRL scale.

As stated in [6], the development of high-tech systems relies on the successful synchronised development of the individual technologies involved. The TRA enables the consistent comparison of maturity among different types of technologies, allowing risk reduction in budget and planning.

A summary of the history and uses of the TRA can be found in [5]. The TRA was originally developed by NASA in the 1980′s (as a tool for communication of technology maturity and for planning). The assessment of technology readiness level is currently being used by the Department of Energy (DOE) [4] and other government agencies in the USA to analyse and manage the technical risk in research and development projects. In Europe, the European Space Agency started using TRA in 2008 and EU Commission is also employing technology readiness levels for funding R&D projects [7] and for innovation and market penetration studies.

This paper presents the TRA of the different systems of IFMIF-DONES. The analysis is intended as a tool for the project management, to identify topics in which more experimental effort should be dedicated. The assessment is based on the documents describing the facility design (IFMIF-DONES Engineering Design Report [8]) and on the outcomes of the performed validation activities. This analysis is intended to be periodically updated, as design and validation activities evolve.

2. Methodology for IFMIF-DONES TRL assessment and validation needs analysis

The IFMIF-DONES project has some special characteristics which affect its Technology Readiness Assessment as well as the expectations regarding the level of maturity of its elements. These are among others:

1. Several components and systems, placed close to the lithium target, operate under a high radiation environment which cannot be reproduced in presently available test facilities.
2. Other central phenomena such as the beam energy deposition in the lithium target cannot be tested before the facility construction.
3. An operational availability of 70 % has been set as a top level goal of the facility. This implies a strict RAMI performance in many components and systems that may not be fully demonstrated at the installation startup, being only achievable after the first operation periods, once the improvements originated from the operational experiences are incorporated.

The features and requirements of IFMIF-DONES that cannot be experimentally proven until the facility is constructed and commissioned (like those mentioned regarding RAMI or related with the beam-target interaction) have not been considered in the present TRL assessment.

2.1. TRL scale

The TRL scale differs slightly depending on the context of the projects assessed [9]. Consequently there are small differences in the TRLs definitions used e.g. by NASA, US DOE, ESA or EU Horizon 2020 and Horizon Europe programmes.

The definitions of Technology Readiness Levels provided in the Technological Readiness Assessment Guides by the United States Department of Energy [4] were used for the first assessment of the IFMIF-DONES systems [10]. The meanings for the first six TRLs from US DOE guides coincide with those used by EU Horizon2020 program [7]. Regarding TRL7, the meaning used in the first case is “Full scale prototype demonstrated in relevant environment” whereas in the second TRL7 is defined as “Full-scale prototype demonstrates full performance in the operational environment; full-scale prototype is similar (not identical) to the actual system”. This last definition has been found more suitable for the IFMIF-DONES systems, for which the difference between engineering to full scale may be not as significant as that between relevant and operational conditions.

Table 1 shows the proposed scale for the assessment of the IFMIF-DONES facility and the meanings of the different TRL levels. This scale has been adapted from [4,7] taking into account IFMIF-DONES particularities. The main adaptations are the following:

- Considering the foreseen staged testing scheme, specially for the accelerator systems, it has been found useful to split TRL6 in two levels, TRL6a and TRL6b, with the following meaning:
- TRL6a: Engineering scale prototype validated with tests in a relevant environment. Full performance not reached.
- TRL6b: Engineering scale prototype validated with tests in a relevant environment. Design conditions reached.

Table 2 outlines the testing requirements necessary to achieve each TRL. Note that the terms (relevant, operational) used in Table 2 to describe the testing environment refer to the test conditions compared with those expected in the real operation of the facility.

2.2. TRL analysis methodology

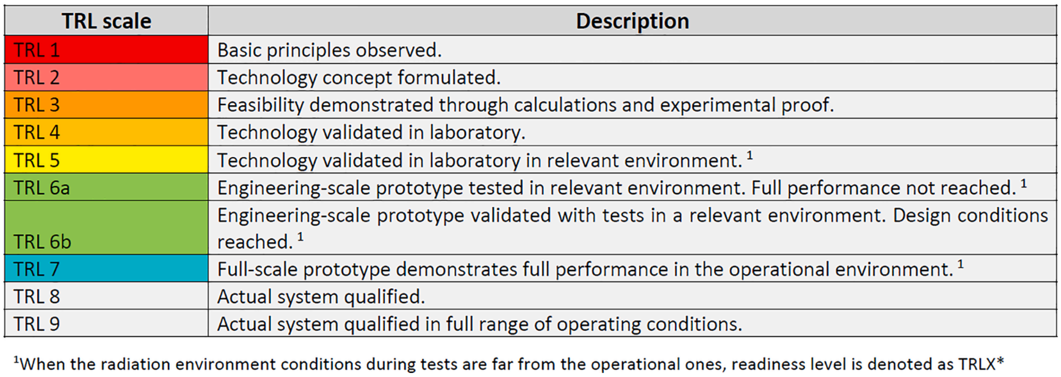
All systems and components (SCs) up to 4th level of the IFMIF-DONES Plant Breakdown Structure [8] have been studied. Those SCs for which available tested commercial solutions exist are considered non-CTEs. A few SCs whose design is in a conceptual or preliminary phase have been excluded from this analysis, as there is not enough definition for evaluating whether they involve CTE or not. Examples of such SCs are the test module PCP pipe bridges and some RH tools for maintenance or for rescuing scenarios in case of accident. In this last case different commercial solutions are being preliminary proposed based on robotic arms, toolboxes and similar technologies. However, integrated designs are necessary to assess whether these solutions fulfil the requirements or special developments or procedures, whose performance should be experimentally demonstrated, are required. A follow-up should be done as the design evolves, to analyze the maturity of the final solutions.

The first TRL evaluation of IFMIF-DONES was carried out in 2016 and focused on Lithium Systems and Test Systems [10]. This evaluation took into account the results from prototyping and tests performed under the IFMIF-EVEDA project [11–14]. It was based on template sheets for each SC which provided the description of the design, the assessment results and relevant references.

In 2021, an update of the status and the outcomes of the validation activities developed under EUROfusion [1,2], IFMIF-EVEDA [12–14] and other projects was performed [15]. The followed methodology involved the compilation of a specific document for each experiment, where a detailed description of the testing carried out, the main lessons learned and the implications in the IFMIF-DONES design were reported and referenced by the experts in charge of the experiments.

The analysis of the maturity of the whole facility has been done based on the most recent design reports at that time and on the above-mentioned information, and in agreement with the coordinators of the different groups of systems. There is always some subjectivity when assigning a given level to a SC and slight changes could occur. Additionally, as design and validation are evolving, the levels change continuously. However, it is noted that the most relevant outcomes of the analysis are the comparison among the results obtained for the different SCs and their evolution with time rather than the exact readiness levels of each SC.

Table 1
TRL scale for the analysis of IFMIF-DONES.



TRL scale	Description
🟥 TRL 1	Basic principles observed.
🟥 TRL 2	Technology concept formulated.
🟧 TRL 3	Feasibility demonstrated through calculations and experimental proof.
🟧 TRL 4	Technology validated in laboratory.
🟨 TRL 5	Technology validated in laboratory in relevant environment. [1]
🟩 TRL 6a	Engineering-scale prototype tested in relevant environment. Full performance not reached. [1]
🟩 TRL 6b	Engineering-scale prototype validated with tests in a relevant environment. Design conditions reached. [1]
🟦 TRL 7	Full-scale prototype demonstrates full performance in the operational environment. [1]
TRL 8	Actual system qualified.
TRL 9	Actual system qualified in full range of operating conditions.

[1] When the radiation environment conditions during tests are far from the operational ones, readiness level is denoted as TRLX*

Table 2
TRL testing requirements for each level.

TRL	Scale of Testing	Fidelity	Environment (except radiation)	Radiation environment	Design Performance
7	Full	Similar	Operational	Operational	Full
7*	Full	Similar	Operational	Not operational	Full
6b	Engineering	Similar	Relevant	Relevant	Full
6b*	Engineering	Similar	Relevant	Not relevant	Full
6a	Engineering	Similar	Relevant	Relevant	Partial
6a*	Engineering	Similar	Relevant	Not relevant	Partial
5	Lab/Bench	Similar	Relevant	Relevant	Partial
5*	Lab/Bench	Similar	Relevant	Not relevant	Partial
4	Lab	Pieces	Simulated		
3	Lab	Pieces	Simulated		
2		Paper			
1		Paper			

Typical Engineering Scale: 1/10 to Full Scale.
The terms (not relevant, relevant, operational) refer to the test conditions in comparison with those expected in the real operation of the facility. Thus, for a component located far from the Li target, where no or very little radiation exists, a relevant or operational environment in the tests means absence of radiation.

2.3. *Target TRL before procurement*

Critical technology elements that must be specifically developed for the IFMIF-DONES project, will reach at most a Technology Readiness Level TRL7 before their procurement. As IFMIF-DONES will be a unique installation, the R&D activities for increasing the maturity of its SCs before their procurement will not aim to achieve TRL8 and TRL9, which are foreseen for a series production. Therefore, only those SCs which are being developed in other fields could reach TRL8 or TRL9 (this last level is equivalent to non CTE).

Target TRL values have been assigned case by case to the different CTEs considering the tests and prototypes that could be realistically performed.

It has been considered that new technologies developed for IFMIF-DONES shall in general reach TRL7 before handover of the design to the entity that will be in charge of the procurements. However, in some specific cases an engineering scale prototype or laboratory tests (TRL5–6) are considered enough for the validation prior to the procurement contract.

2.4. *Determination of required validation activities*

After completing the TRL analysis of the whole facility and establishing the target TRLs for each component, the experimental validation activities needed to increase the maturity of the IFMIF-DONES SCs up to the level required for launching their procurement have been compiled. The SCs requiring validation are those whose assessed TRL values are lower than the target TRL.

The needed R&D activities have then been obtained by compiling all the design and validation information performed on the systems up to the present TRL assessment. Technical coordinators of the different groups of systems have provided their expert advice, proposals and judgment for this task.

It must be noted that there are some required validation activities that do not come out from this TRL study of individual SCs, being motivated by open issues related to project transversal activities (safety, neutronics, control, RAMI) and affecting several SCs of the facility.

3. Results of the TRL analysis

The Building and Auxiliary SCs are mostly commercial. Although, as mentioned in Section 2.2, a revision of maturity state must be done in some systems whose designs are still preliminary, currently only certain components of the Remote Handling Systems are considered CTEs and require further validation. These are custom-design devices devoted to the replacement and maintenance of specific components, mainly related to Lithium and Test Systems, requiring high positioning precision, high payload, and ability to work under harsh conditions. Those include the Twin Manipulator, designed for operations within the Test Cell Lithium System Interface Cell (sealing replacement); the Parallel Kinematic Manipulator, dedicated to operations of in-vessel components within the Test Cell; and the Lithium cleaning machine.

Regarding Test, Lithium and Accelerator Systems, the results are summarized in Tables 3, 4 and 5, respectively. These tables present for each SC its Product Breakdown Structure (PBS) identification number and name and the evaluated TRL value, employing the colour code shown in Table 1. The Target TRL values before procurement are also shown in the last column of the Tables. Note that non-CTEs or those CTEs which have already reached the target TRL are not shown in the Tables.

As mentioned in Section 2.2, the evaluated TRL values are evolving thanks to the ongoing validation activities. Therefore present TRL values could be higher than those shown in the tables, which correspond to the date when the analysis [15,16] was performed.

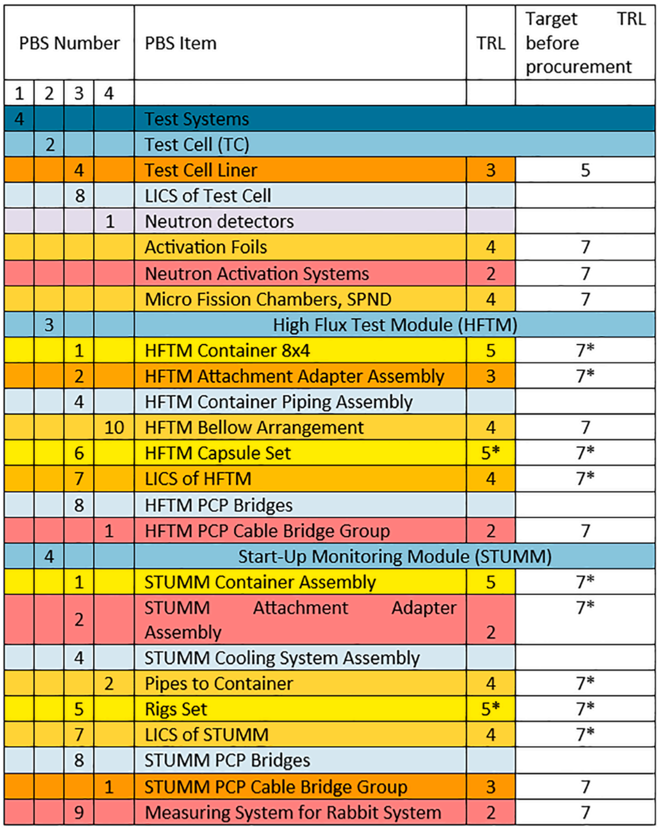
A summary of the conclusions reached is presented in the following subsections. The results of the full TRL analysis and the consequent required validation activities are included in [16].

3.1. *Test systems*

One of the main issues for the Test Systems is the unprecedented operational environment, for which it is difficult to predict the

Table 3

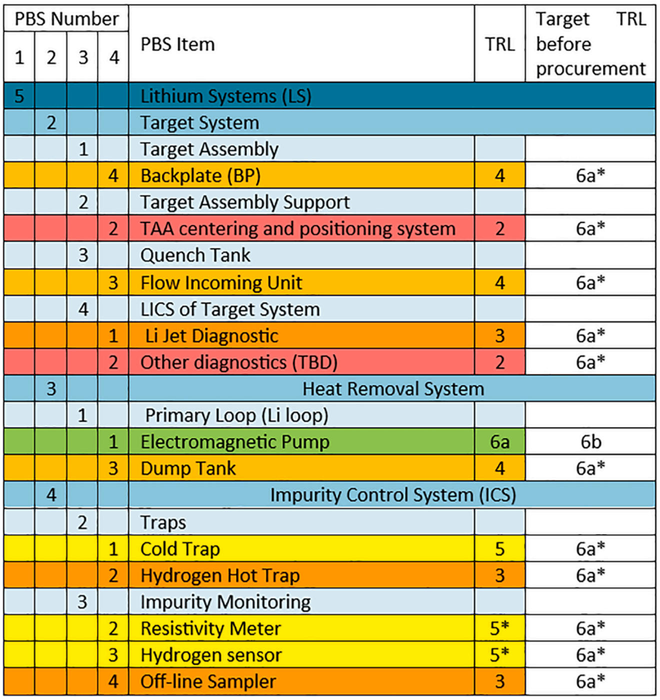
CTE of Test systems requiring further validation.



PBS Number				PBS Item	TRL	Target TRL before procurement
1	2	3	4			
4				Test Systems		
	2			Test Cell (TC)		
		4		Test Cell Liner	3	5
		8		LICS of Test Cell		
			1	Neutron detectors		
				Activation Foils	4	7
				Neutron Activation Systems	2	7
				Micro Fission Chambers, SPND	4	7
	3			High Flux Test Module (HFTM)		
		1		HFTM Container 8x4	5	7*
		2		HFTM Attachment Adapter Assembly	3	7*
		4		HFTM Container Piping Assembly		
			10	HFTM Bellow Arrangement	4	7
		6		HFTM Capsule Set	5*	7*
		7		LICS of HFTM	4	7*
		8		HFTM PCP Bridges		
			1	HFTM PCP Cable Bridge Group	2	7
	4			Start-Up Monitoring Module (STUMM)		
		1		STUMM Container Assembly	5	7*
		2		STUMM Attachment Adapter Assembly	2	7*
		4		STUMM Cooling System Assembly		
			2	Pipes to Container	4	7*
		5		Rigs Set	5*	7*
		7		LICS of STUMM	4	7*
		8		STUMM PCP Bridges		
			1	STUMM PCP Cable Bridge Group	3	7
		9		Measuring System for Rabbit System	2	7

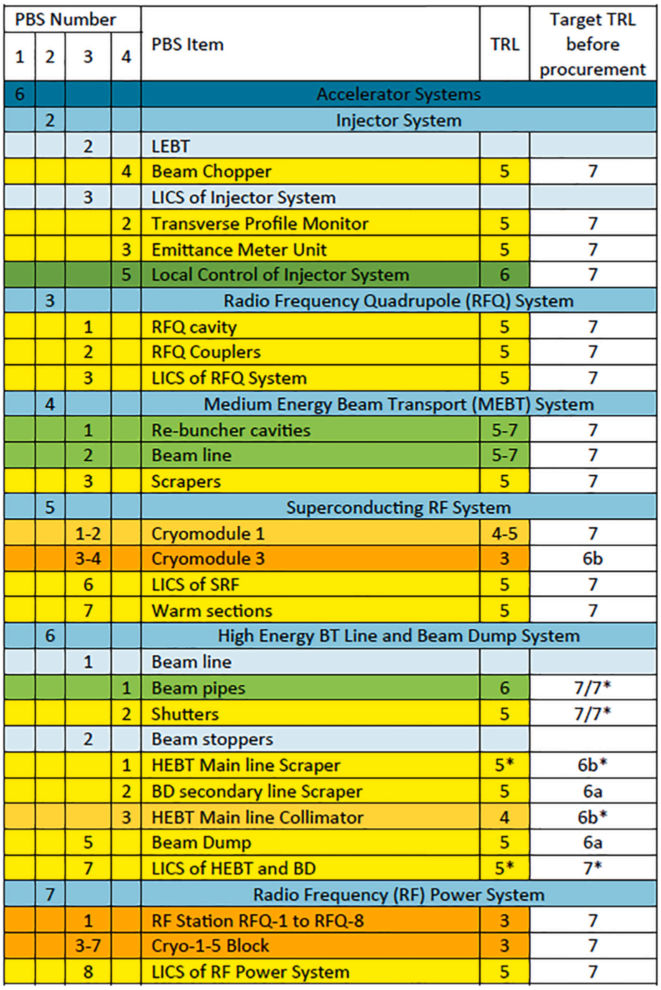
Table 4

CTE of lithium systems requiring further validation.



PBS Number				PBS Item	TRL	Target TRL before procurement
1	2	3	4			
5				Lithium Systems (LS)		
	2			Target System		
		1		Target Assembly		
			4	Backplate (BP)	4	6a*
		2		Target Assembly Support		
			2	TAA centering and positioning system	2	6a*
		3		Quench Tank		
			3	Flow Incoming Unit	4	6a*
		4		LICS of Target System		
			1	Li Jet Diagnostic	3	6a*
			2	Other diagnostics (TBD)	2	6a*
	3			Heat Removal System		
		1		Primary Loop (Li loop)		
			1	Electromagnetic Pump	6a	6b
			3	Dump Tank	4	6a*
	4			Impurity Control System (ICS)		
		2		Traps		
			1	Cold Trap	5	6a*
			2	Hydrogen Hot Trap	3	6a*
		3		Impurity Monitoring		
			2	Resistivity Meter	5*	6a*
			3	Hydrogen sensor	5*	6a*
			4	Off-line Sampler	3	6a*

Table 5
CTE of the Accelerator requiring further validation.



PBS Number				PBS Item	TRL	Target TRL before procurement
1	2	3	4			
6				Accelerator Systems		
	2			Injector System		
		2		LEBT		
			4	Beam Chopper	5	7
		3		LICS of Injector System		
			2	Transverse Profile Monitor	5	7
			3	Emittance Meter Unit	5	7
			5	Local Control of Injector System	6	7
	3			Radio Frequency Quadrupole (RFQ) System		
		1		RFQ cavity	5	7
		2		RFQ Couplers	5	7
		3		LICS of RFQ System	5	7
	4			Medium Energy Beam Transport (MEBT) System		
		1		Re-buncher cavities	5-7	7
		2		Beam line	5-7	7
		3		Scrapers	5	7
	5			Superconducting RF System		
		1-2		Cryomodule 1	4-5	7
		3-4		Cryomodule 3	3	6b
		6		LICS of SRF	5	7
		7		Warm sections	5	7
	6			High Energy BT Line and Beam Dump System		
		1		Beam line		
			1	Beam pipes	6	7/7*
			2	Shutters	5	7/7*
		2		Beam stoppers		
			1	HEBT Main line Scraper	5*	6b*
			2	BD secondary line Scraper	5	6a
			3	HEBT Main line Collimator	4	6b*
		5		Beam Dump	5	6a
		7		LICS of HEBT and BD	5*	7*
	7			Radio Frequency (RF) Power System		
		1		RF Station RFQ-1 to RFQ-8	3	7
		3-7		Cryo-1-5 Block	3	7
		8		LICS of RF Power System	5	7

performance of the systems and components and that makes compulsory the use of RH systems for their handling.

Regarding the Test Cell, the procedure for welding the liner penetrations should be tested and qualified.

Several prototypes and experimental tests of irradiation modules have been performed under IFMIF/EVEDA [17] and EUROfusion projects. A prototype of the High Flux Test Module (HFTM) (PBS 4.3) with one-fourth of the width was tested at 1:1 helium conditions, achieving the full temperature range 250 – 550 °C in heated capsules (with and without surrogate for volumetric heating). Filling of specimens and NaK liquid metal into capsules and their hermetic closing was performed, as well as retrieval and cleaning of the specimens. Lessons learned were incorporated into the HFTM design pursued within the WPENS activities. Table 3 shows the current TRL status and the target one before procurement. The main remaining validation activities required are listed below:

- Tests of HFTM prototype (PBS 4.3) under pressurized He operating conditions, to be performed at HELOKA-LP (KIT) [18]. These tests will demonstrate the performance not only of capsules and container, but of the whole module in terms of maximum deformations, temperature control, vibrations, etc.
- Handling of the irradiation modules during their installation, alignment and removal. The remote connection operations at both sides of the Piping and Cabling Plug cable bridge (PBS 4.3.8) are considered specially critical given the large number of cables in a small space. The electric connectors for the irradiation modules will be similar to those of the Target Assembly. A prototype will be irradiated at MARIA reactor [19].
- Long term endurance/lifetime tests of a capsule (PBS 4.3.6).
- Radiation tests of heaters at MARIA reactor, to validate both the wire and the isolation (PBS 4.3.6).
- Capsule filling with sodium and extraction of sodium from the capsules (PBS 4.3.6), emulating the operation in a hot cell.

A programme for qualifying radiation detectors for the IFMIF-DONES spectrum and requirements is ongoing (PBS 4.2.8). This must clarify the time response of micro-fission chambers and their performance at high temperature among other topics. It includes also the validation of self-powered neutron detectors for fast neutrons and tests of their operation inside sodium. For the case of the Start-up Monitoring Module (STUMM) (PBS 4.4), the response of numerous detectors in a small space will be investigated with and ad-hoc prototype and the performance of the Rabbit system (PBS 4.4.9) with the complicated geometry required should also be checked.

Other issues to be investigated are the achievable variability among individual ˙identical˙ detectors and the effect of the radiation absorbed dose and dose rate on the thermocouple measurements.

3.2. Lithium systems

Many of the components of the Lithium Systems were tested thanks to the construction and operation of the ELTL loop [11,17] during the IFMIF-EVEDA project under the Broader Approach Agreement between Europe and Japan. This loop was an engineering scale prototype of the IFMIF-DONES main Li loop where the vertical dimensions and the height of the loop were equal to those of IFMIF-DONES, but the width of the Li target was scaled down by a factor 2.6 and consequently the flow rate and the volume of the circulating Li were reduced in the same extent. Other experiments have been done at Lifus 6 loop [20] (on steel corrosion by Li, on Li purification from Nitrogen and on impurities monitoring through online and offline techniques), DRP [21] (on RH procedures for Target Assembly replacement) and other facilities.

The ELTL operation demonstrated three key subjects: the hydrodynamic stability of the Li jet, the operation of the cold trap (PBS 5.4.2.1) and the long-time operation of the Target Assembly (PBS 5.2.1) and of the loop (PBS 5.3.1). In spite of this, it must be emphasized that the tests did not include the radiation environment nor the interaction with the beam. Moreover, some relevant components of the Lithium Systems, in particular some traps and monitors of the Impurity Control System (PBS 5.4.3), were not tested.

Thanks to the ELTL experiments TRL values for the Lithium Systems are quite high. Table 4 shows the present and target TRL for the systems requiring further validation. The remaining validation activities are focused on those elements that were not tested at ELTL, on the qualification of components under relevant irradiation conditions and on the analysis of their RH compatibility.

The Target Assembly (PBS 5.2.1) is foreseen to be replaced at IFMIF-DONES on an annual basis due to its expected degradation under the harsh working environment. Given the complexity of the required installation and alignment operations these should also be tested with a mockup. Partial tests were done at ENEA but more comprehensive tests with a mockup representative of the final design are recommended. Testing of prototypes of the Fast Disconnection Systems (belonging to PBS 5.2.1) at the interfaces of the Target Assembly with the beam ducts and the lithium pipes (including collar, bellows and actuation systems), are planned to demonstrate their functionality and foreseen lifetime. RH actuators, gearboxes, gaskets and bellows should be qualified under irradiation (related to PBS 5.2).

Experiments are also needed to check the performance of the proposed Li jet diagnostics and the feasibility of measuring the jet thickness during facility operation with the required precision.

Regarding the Heat Removal System, the electromagnetic pump (PBS 5.3.1.1) required for IFMIF-DONES is not standard, although a reduced scale one was tested at ELTL. An ad-hoc design has been done and experimental validation of the performance of a prototype is planned, including the testing of solutions to extend its coastdown time to meet safety requirements. Some tests have been performed already in sodium circuits. Radiation induced degradation of the magnet should also be investigated. With respect to the oil used to extract the heat from the primary Li loop, qualification under irradiation, measuring the changes in cooling capacity, composition, compatibility with surrounding materials and reactivity with Li, is ongoing. Experiments to study the reactivity of lithium under different atmospheres are also planned with the aim of validating the simulations of possible off-normal events.

Finally, regarding the traps (PBS 5.4.2) and monitors for impurity control (PBS 5.4.3), after experiments in Lifus 6 and theoretical analysis several possible getter materials for the Nitrogen trap (embedded into the Dump Tank PBS 5.3.3) have been selected and are currently under investigation in a dedicated facility (ANGEL). The cold trap was tested at ELTL and Lifus6 loops but further tests are needed to investigate the retention of relevant radioisotopes such as ^{7}Be and ^{54}Mn and to estimate the trap lifetime. These will be addressed in a new Li loop named LITEC, presently under construction by CIEMAT, with IFMIF-DONES-relevant size and operational parameters, which is intended to provide the integral validation of the Impurity Control System design. Measurements of the efficiency of the Hydrogen trap and investigation of H desorption are also planned. Experimental measurement of mass transfer coefficients and further investigations of corrosion rates are also needed for validating simulation codes analyzing the distribution of Activated Corrosion Products (ACPs) and other radioisotopes (^{7}Be) in the loop. The main monitoring technologies (resistivity meter, H sensor and off line measurements) will be also qualified at LITEC.

New experiments to understand the lithium reactivity with different atmospheres are also planned to validate simulations of off-normal events.

3.3. Accelerator systems

The IFMIF-DONES accelerator [22] has unprecedented characteristics (very high continuous current – 125 mA of 40 MeV deuterons). It will be validated with the operation of its prototype Linear Prototype Accelerator (LIPAc) [13,14], identical to the lower energy part of the IFMIF-DONES accelerator (up to 1st cryomodule included), which is being tested at Rokkasho (Japan).

The LIPAc accelerator is being commissioned in sequential phases involving beam experiments with the injector, Radio Frequency Quadrupole (RFQ), and cryomodule, with progressively increasing current and duty cycle. Therefore, the different accelerator elements are presently at different stages of the validation and consequently they have different TRL values. The results of the performed analysis are shown in Table 5. The validation will be completed in the next years when full parameters will be reached. The need of some improvements (e.g. at the injector and RF systems) has already come up from the experiments performed up to now. These improvements should be validated in LIPAc or other facilities.

As all LIPAc components (including ion source, RFQ, Medium Energy Beam Transport (MEBT) line, Superconducting Radio Frequency (SRF) linac, High Energy Beam Transport (HEBT) line, diagnostics and beam dump) have already been manufactured and factory acceptance tests have been successfully passed, it can be considered that laboratory validation has been performed for all of them.

Moreover the beam tests performed at Rokkasho have already validated the ion source whereas validation of RFQ (PBS 6.3), MEBT (PBS 6.4) and diagnostics with beam is presently ongoing. Regarding the Target TRL values, those components whose design will be identical to the LIPAc one, should reach TRL 8 after LIPAc tests with full continuous current. However, in most cases the design will be improved by incorporating the lessons learned, and therefore the achieved TRL will be 7 at most.

Apart from LIPAc, specific R&D activities are needed regarding elements not included in the accelerator prototype, such as:

- RF power sources (PBS 6.7): the solution chosen for IFMIF-DONES is based on solid-state amplifiers [23] whereas that of LIPAc is presently based on tetrode tubes.
- The three last cryomodules (PBS 6.5.3 & PBS 6.5.4) [24], which use a different cavity design (high-beta cavity) compared to that of the LIPAc cryomodule and whose power coupler design presents also some differences.
- The HEBT line (PBS 6.6) [25], which in IFMIF-DONES is longer and more complex, as it must transport the beam from the linac exit up to the lithium target conforming its shape to the needed footprint geometry at the target. The line includes several radiation shutters, beam stopping devices and instrumentation with stricter RAMI and RH requirements than the equivalent components at LIPAc. It also includes some safety components like fast valves, which should act in case of an abnormal event and other CTEs like a kicker magnet.

There are as well issues that LIPAc can not address such as the influence of IFMIF-DONES radiation on the beam instrumentation and on the elements located close to the target.

Systems and components related with these issues have at present a relatively low TRL. Experimental activities such as the validation of solid state RF power sources (PBS 6.7), testing of high-beta cavity and its RF coupler (included in PBS 6.5), tests of fast valve (PBS 6.8), beam instrumentation (mostly included in PBS 6.6.7), etc. are presently being performed.

4. Summary and conclusions

This paper explains the methodology applied to perform a Technology Readiness Assessment of IFMIF-DONES and to identify in a systematic way the elements requiring further validation and the pending validation activities. This analysis is intended as a project management tool and will be periodically updated.

Plant Systems related technologies are mostly commercial. Regarding the Test Systems, among other R&D activities, there is a need of further developments of neutron detectors adequate for DONES requirements. Most of the validation activities of Lithium Systems are focused on the purification technologies which are foreseen to be validated in a dedicated Li loop. Finally, the DONES accelerator is being validated with the operation of its prototype LIPAc and specific activities are ongoing regarding DONES elements not included in it, such as the three last cryomodules and the HEBT line.

There are some issues that cannot be validated before the construction of IFMIF-DONES. An example is the operation of the lithium target with the deuteron beam, for which the first tests will take place during the commissioning of the facility. The operational experience acquired during this phase will be used to validate some technologies and to trigger some modifications to improve the device. Apart from those, most of the pending validation activities are already launched under Eurofusion WPENS or covered by research units collaborating with the IFMIF- DONES Project.

CRediT authorship contribution statement

B. Brañas: . **J. Maestre:** Writing – original draft. **D. Bernardi:** Supervision, Writing – review & editing. **A. Ibarra:** Project administration, Writing – review & editing. **F. Arbeiter:** Writing – review & editing. **P. Arena:** Investigation. **F. Arranz:** Writing – review & editing. **S. Becerril:** Writing – review & editing. **M. Cappelli:** Writing – review & editing. **S. Chel:** Investigation. **J. Castellanos:** Writing – review & editing. **P. Favuzza:** Investigation. **D. Jiménez-Rey:** Investigation. **W. Krolas:** Writing – review & editing. **F. Martin-Fuertes:** Writing – review & editing. **G. Micciché:** Writing – review & editing. **F.S. Nitti:** Writing – review & editing. **I. Podadera:** Writing – review & editing. **Y. Qiu:** Writing – review & editing. **D. Regidor:** Investigation. **B. Renard:** Investigation. **T. Tadic:** Investigation. **R. Varela:** Writing – review & editing. **M. Weber:** Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

B. Branas reports financial support was provided by European Consortium for the Development of Fusion Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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