CONFERENCE PRE-PRINT

OVERVIEW OF THE DONES EXPERIMENTAL PROGRAMME

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Abstract

The International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES) is a cutting-edge research infrastructure designed to test and qualify materials under neutron irradiation conditions similar to those expected in future fusion reactors [1]. Currently under construction in Escúzar, Spain, IFMIF-DONES plays a pivotal role in the European roadmap for fusion energy, aiming to bridge critical gaps in material science and other fusion technologies, essential for the development of fusion power plants. As a first-of-its-class, high-flux, fusion-like neutron source, IFMIF-DONES features outstanding experimental capabilities, enabling both fusion-oriented and non-fusion-oriented experiments using neutrons and deuterons [2].

To meet the required experimental capabilities, this infrastructure will feature the most intense continuous-wave linear accelerator in the world, ranking among the most powerful ever built. It will include the largest liquid lithium circuit and a unique experimental target, where a 5 MW (with a possible upgrade to 10 MW), 40 MeV, 125 mA deuteron beam will impinge on a liquid lithium curtain flowing at 15 m/s, embedded within a modularly shielded test cell. The facility will also incorporate two dedicated rooms for complementary deuteron- and neutron-based experiments, requiring advanced technologies such as deuteron beam extraction from the accelerator to expand the range of experimental capabilities [3]. Beyond fusion, the facility is expected to support nuclear physics research, radioisotope production, and broader scientific investigations.

The DONES Programme is primarily dedicated to generating irradiation test data for the design, licensing, construction, and safe operation of the fusion demonstration power plant (DEMO). This involves developing a comprehensive database of fusion-like neutron irradiation effects on materials, facilitating radiation response benchmarking, and advancing computational material science models to validate and enhance predictions of material behaviour as well as additional contributions to other fusion technologies with special emphasis on tritium technologies ones. To fulfil these objectives, the programme is focused on providing a high-energy neutron source with sufficient intensity and irradiation volume to simulate the fusion environment. Additionally, testing of tritium breeding blanket concepts will be an integral part of the research activities. This work outlines the experimental capabilities of the facility, the current construction status in Escúzar, and the systematic approach taken to structure the experimental programme, define irradiation conditions, and validate critical technologies.

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1. INTRODUCTION

Significant progress has been achieved during the first years of the construction phase, which formally started on 16 March 2023. On the one hand DONES Programme Team has been stablished and the DONES Programme management setup based in an innovating organization is already running. On the other hand, several relevant prototypes have been installed in partner laboratories and also at the Escúzar site, to support the licensing, safety, and construction of the first buildings of the IFMIF-DONES facility. Furthermore, major contracts have been awarded for technical and engineering assistance, project integration, safety engineering, and essential accelerator and test cell systems, including the Programme Lifecycle Management implementation. The main building construction contract is under tendering and to be awarded in 2025, with civil works commencing soon.

From a programme experimental standpoint, IFMIF-DONES facility is designed to accommodate a wide range of experimental activities, including fusion-related experiments focused on materials characterization with reloading capacity, breeding blankets testing and divertor components evaluation under fusion-relevant conditions, and other irradiation modules for further testing. The test facilities are also ready for complementary research activities encompassing studies in nuclear physics, medical applications, and industrial research, thereby broadening the scientific scope of the infrastructure.

To define a first draft of a technical experimental programme, IFMIF-DONES works in close collaboration with the DONES Users Community, an international assembly of scientists and engineers actively involved in the identification and preparation of experiments at the facility, encompassing both fusion and non-fusion applications. DONES Users Workshops are held on yearly basis to discuss experimental needs, propose research applications, and review progress.

A first proposal of the IFMIF-DONES experimental programme is being discussed to address the most relevant needs for fusion materials research. It will be coordinated by the DONES Programme Team in liaise with the different stakeholders and will integrate the proposal of the Users community. It has been established, focusing on defining irradiation priorities, optimizing irradiation matrices, and fostering a robust user community. Initial experiments will focus on irradiation of reduced activation ferritic martensitic (RAFM) steels like EUROFER97 and similar candidates, assessing their performance under high neutron flux to validate their application in fusion reactors. The experimental plan will maybe also include irradiation experiments to investigate tritium behaviour in breeding blanket systems to ensure efficient tritium production and recovery.

These initial experiments are designed to establish a solid foundation for subsequent research activities, ensuring that IFMIF-DONES fulfils its mission of advancing fusion energy development. Standing at the forefront of fusion materials research, IFMIF-DONES Facility provides unprecedent capabilities to simulate the extreme conditions of future fusion reactors. Planed test and qualification activities will play a crucial role in the licensing of fusion power plants.

2. PROGRESS AND CURRENT STATUS

The DONES Programme is built around the in-kind contributions of international partners. Currently, institutions from Spain, Croatia, Japan and the European Union are agreed parties, pending formal agreement signature in November 2025. Italy has signed a Memorandum of Understanding (MoU), and Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Latvia, Lithuania, Romania, Slovakia, Slovenia, and Ukraine participate as observers, showing their interest in exploring future membership of the Programme with different levels of progress.

The IFMIF-DONES facility is not only a technological challenge but also a strategic project for the development of fusion energy, classified as “Indispensable” for commercial fusion energy in the EUROfusion Facility Review carried out in 2023.

After the start of the construction phase in March 2023, the first buildings at the IFMIF-DONES site are already completed as shown in Fig.1. The first phase of buildings construction has been developed by CIEMAT. At the same time, the University of Granada has built the UGR-DONES research centre next to the facility to support the DONES Programme.

Figure 1. Current status of civil works on the IFMIF-DONES site

The IFMIF-DONES Main Building will host the components of the neutron source and will be supported by auxiliary buildings accommodating systems such as electric power supply and cooling. The Main Building is designed with a volume of 160 × 80 × 34 meters, with approximately 20 meters above ground level and one floor buried to improve performance. Several tenders for the construction of these buildings have been awarded or are under evaluation, with the objective of starting the main civil works in the coming months.

Tenders related to most of the main components of the accelerator and the test cell are also under execution. Framework contracts are active to support the project in areas such as safety, specific engineering disciplines, and Plant Lifecycle Management (PLM).

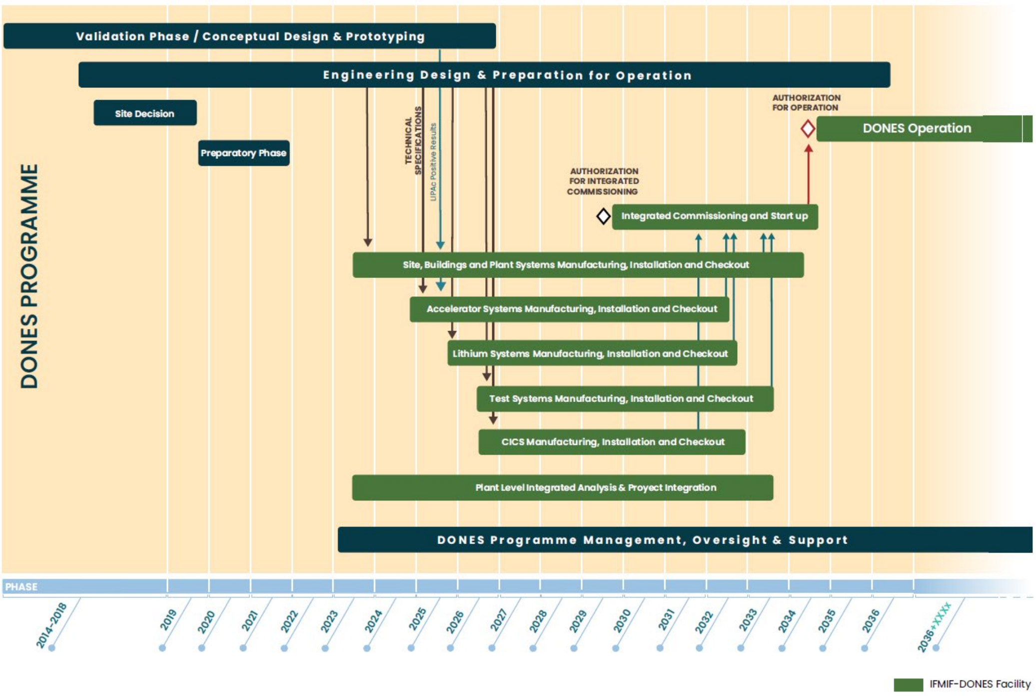

Figure 2. DONES Programme updated Master Schedule

In the last two years, an innovative organizational structure has been implemented. The so-called DONES On-site Joint Team integrates members of the Programme Team and the IFMIF-DONES España Consortium to work together in the daily management of the project accomplishing both of their respective mandates.

As shown in Fig. 2, the different steps of the IFMIF-DONES construction phase started progressively in 2023. The Integrated Commissioning and Start-up is scheduled for 2029, while the beginning of regular operation is expected in 2034.

3. ONSITE VALIDATION ACTIVITIES AND RECENT EXPERIMENTAL RESULTS

During the Validation and Engineering Design phases (2006-2025), tens of prototypes have been developed to reduce technological risk of the DONES Programme. In the last years several of them have been developed to be installed on the IFMIF-DONES site so that relevant validation activities could start onsite as soon as possible. Currently three validation experiments are installed in the UGR-DONES research centre, aside IFMIF-DONES site.

These laboratories shown in Fig.3 are in different status. While LITEC (Lithium Technologies CIEMAT) is under construction, Start-Up Monitoring Module (STUMM) Proto has been just commissioned and is starting experimental phase, and Multipurpose Vacuum Accident Scenarios (MuVacAS) has been running for one year and first experimental results are available and summarized in the next section.

Complementary to the onsite validation experiments, other prototypes are delivering experimental results with different funding, like LIPAc [4] prototype accelerator under the Broader Approach agreement (BA) and those under EUROfusion work programme Early Neutron Source (WPENS), for which the Permanent Magnet Pump (PMP) electromagnetic pump is an example with some results shown in the next section.

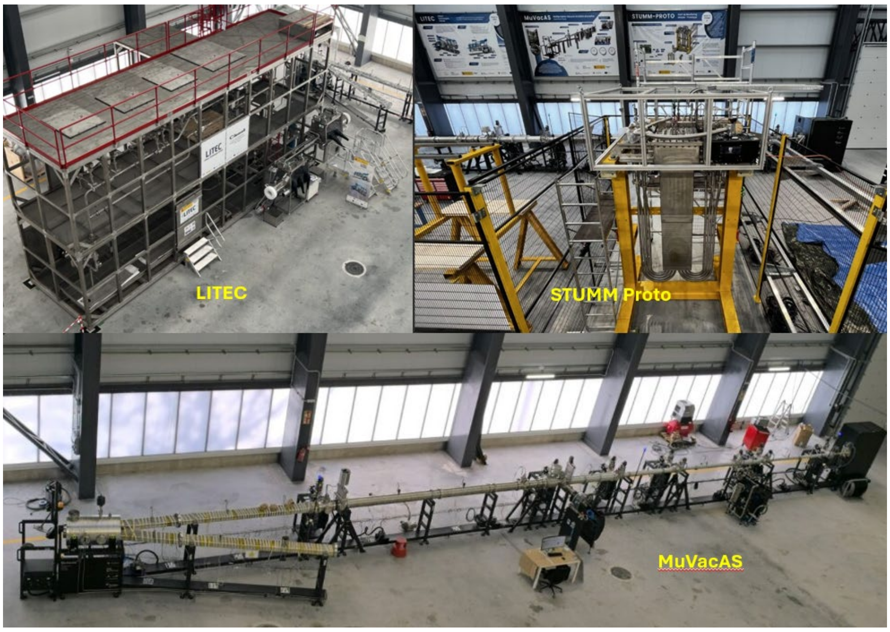

Figure 3. On-site validation experiments (MuVacAS, STUMM Proto and LITEC)

MuVacAS Experimental Setup

From a safety engineering perspective, there are no existing Spanish safety standards that fully align with the unique design of IFMIF-DONES. Consequently, the adopted approach is to comply with the regulations governing nuclear facilities in a adapted approach linked to the facility risks, even though these are not strictly mandatory for IFMIF-DONES. This methodology requires extensive documentation and analysis for licensing, ensuring that all potential failure modes are considered so that even in highly unlikely scenarios, the facility remains in a safe state, covering the protection of personnel, the facility, and the environment.

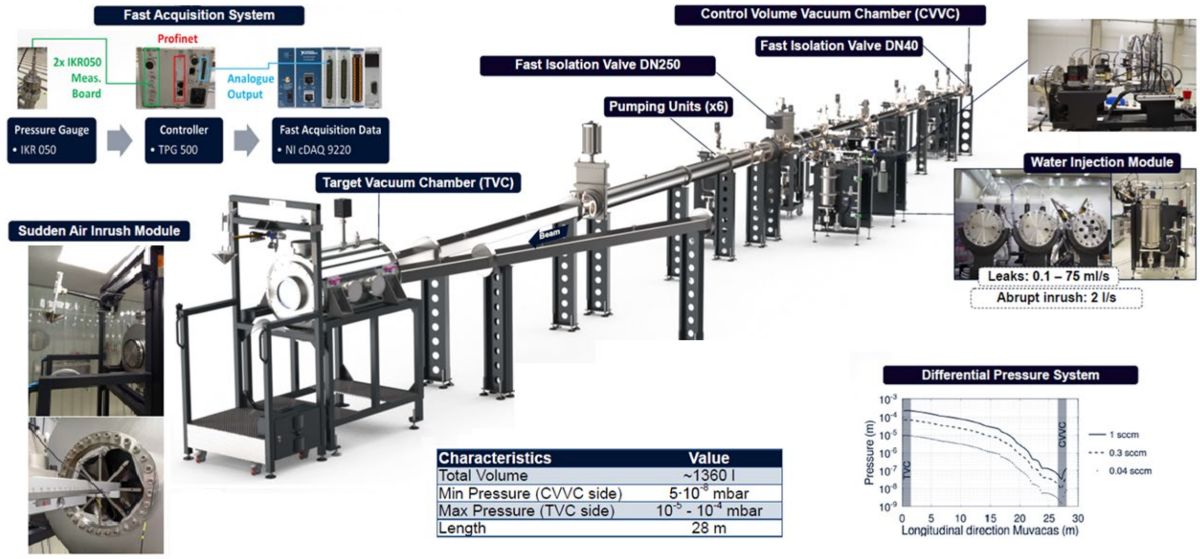

Figure 4. MuVacAS Experimental Setup and its experimental modules.

The Multipurpose Vacuum Accident Scenarios (MuVacAS) is an experimental facility developed to study and characterize Loss of Vacuum Accidents (LOVAs) under conditions representative of high-power particle accelerator environments, such as those found in IFMIF-DONES. According to deterministic analyses [5,6]. Its main objective is to provide high-quality experimental data to support the safety engineering design and to assess the risks associated with vacuum loss accidents in beamlines, vacuum vessels, and validate the safety credited mitigation measures such as the Fast Safety Isolation Valves (FSIVs).

The MuVacAS facility scheme, shown in Fig. 4, recreates as reasonably as possible the characteristics and specifications of the last 49 meters of the accelerator and target vacuum chambers of IFMIF-DONES. It can reach pressures in the range of 10−3 to 10−8 mbar, and is connected to auxiliary systems that enable controlled accident scenarios. MuVacAS is designed to reproduce various types of LOVA scenarios, such as progressive leaks (simulating cracks or valve failures), water ingress into vacuum lines (representing potential cooling system leakages), rapid air inrushes due to sudden loss of vacuum, and differential vacuum chambers. The experimental setup is fully instrumented with vacuum gauges, flow meters, the experimental modules, triggers, accelerometers, and strain gauges, all connected to a synchronized fast data acquisition system (25 kHz). This instrumentation allows for precise monitoring of transient phenomena during each test.

Two preliminary results of the demonstrated capabilities of MuVacAS obtained in the recent experimental campaigns are presented below. Each test provides valuable insight into the dynamic behaviour of the system, including pressure wave propagation, gas flow distribution, actuation times for the mitigation components, and effectiveness of the Fast Safety Isolation Valve against LOVA scenarios.

Case A results – Recreation of LOVA as safety analysis approach.

A loss of vacuum in the Target Vacuum Chamber (TVC) may occur due to rupture of the back plate (BP), driven by two competing phenomena. First, rupture of the back plate (BP) which is a thin plate separating neutron production (under vacuum) from neutron irradiation areas disrupts the lithium layer and allows helium from the target chamber atmosphere to enter, exposing the BP to potential beam damage (melting and vaporization, releasing radioactive material). Second, helium propagation towards the cryomodules quenches the beam and prevents further acceleration. These passive effects stop beam operation by either gas interaction in the beam duct or disruption of cryomodule performance.

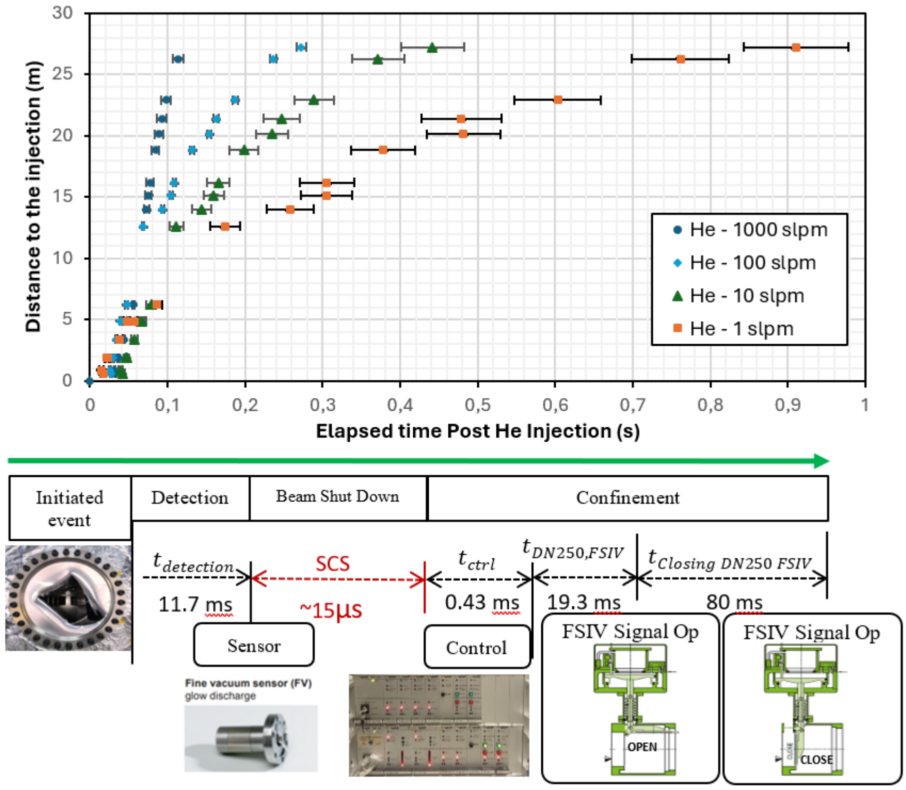

Figure 5. Top: Wavefront detection along the MuVacAS line in the case of unmitigated scenario for various He flow rates in the MuVacAS system. Bottom: Estimation of the event times for the IFMIF-DONES safety analysis according to the mitigated scenario.

In the unmitigated case, the mobilizable material consists of BP, which includes 1% of AC/ACP and 100% of tritium from that 1% (conservative assumption), without any credited confinement. Public dose estimates reach 0.15 mSv, high enough to justify scenario mitigation. Preliminary results [5] show that helium propagation varies as function of the leak size, and the estimation for IFMIF-DONES scenarios enabling passive beam shutdown in 250 ms. In the mitigated case, FSIV effectiveness is estimated at ~99%. Actuation times of the safety systems, extracted from the experiments, are summarized in Fig. 5. Future studies will focus on obtaining reliability values for critical components and to assess the architectures of integrated safety control systems.

Case B results - Deep Reinforcement Learning as control agent.

In this preliminary result a fully data-driven approach for autonomous pressure control is presented. A Deep Learning Surrogate Model, trained on real operational data, emulates the dynamics of the argon injection system [7]. This high-fidelity digital twin then serves as a fast-simulation environment to train a Deep Reinforcement Learning agent.

The results shown in Fig. 6 demonstrate that the agent successfully learns a control policy that maintains gas pressure within strict operational limits despite dynamic disturbances. This approach marks a significant step toward the intelligent, autonomous control systems required for the demanding next-generation particle accelerator facilities.

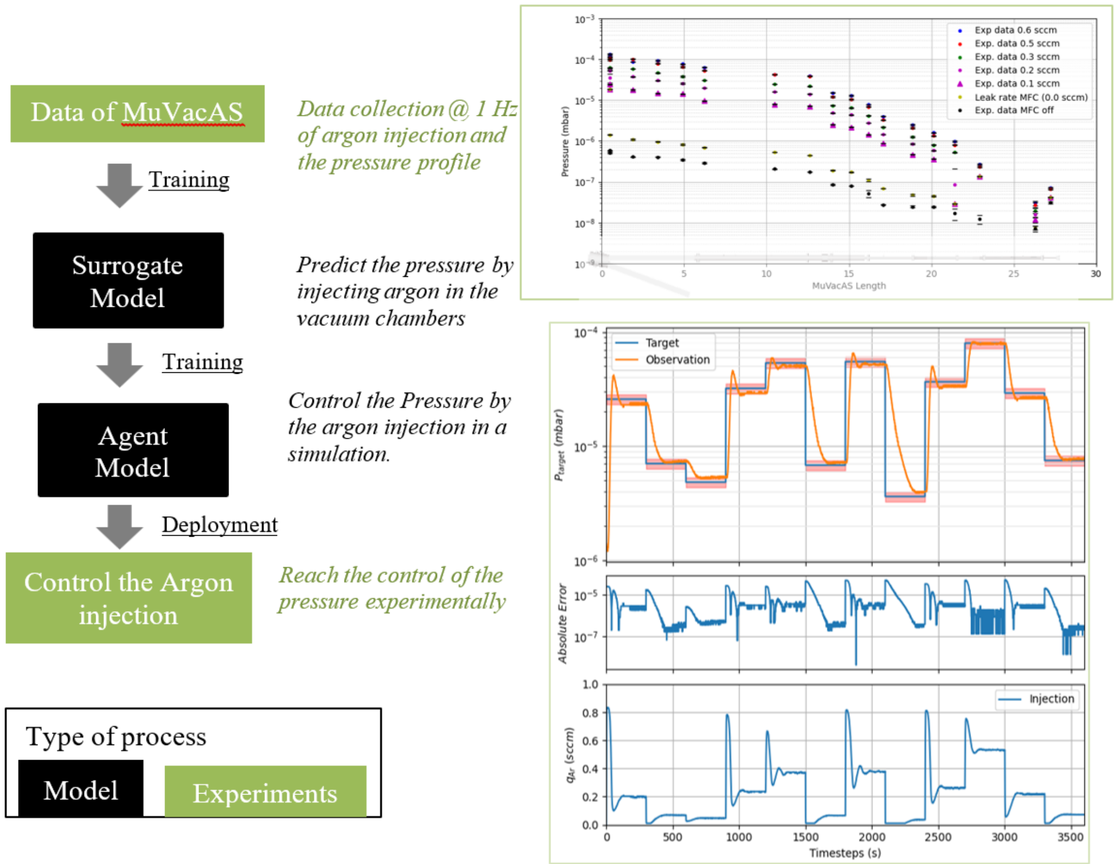

Figure 6. Flow chart of the Deep Reinforcement Learning implementation in MuVacAS.

Permanent Magnet Pump (PMP)

In the IFMIF-DONES facility, the circulation of liquid lithium in the primary loop [8] is ensured by a Permanent Magnet Pump (PMP), a type of Electro Magnetic Pump (EMP) optimized for high reliability and efficiency under demanding conditions. The design of this EMP is particularly challenging due to the strict performance requirements and severe operating conditions, including the need to deliver 100 L/s flow of liquid lithium (at 350ºC) at an output pressure rise of 4 bar while operating with a very low inlet pressure of about 0.3 bar. The pump employs permanent magnets arranged in a Halbach array to generate the magnetic field, eliminating windings and their associated risks of overheating or insulation failure. It is driven by a 160 kW AC motor coupled to a flywheel, which provides the necessary inertia to ensure long coast-down times and maintain the lithium jet across the target in case of a sudden stop.

Numerical and experimental validation

The hydraulic channel has been carefully optimized to meet these requirements, evolving from an earlier three-channel prototype to a five-channel configuration with perforated inner walls to improve current closure and magnetohydrodynamic performance. Numerical simulations confirmed that the pump achieves the required flow and pressure. In addition, a prototype of the EMP has been constructed to validate the design through an exhaustive experimental campaign. Fig.7 shows the prototype integrate in a sodium loop facility.

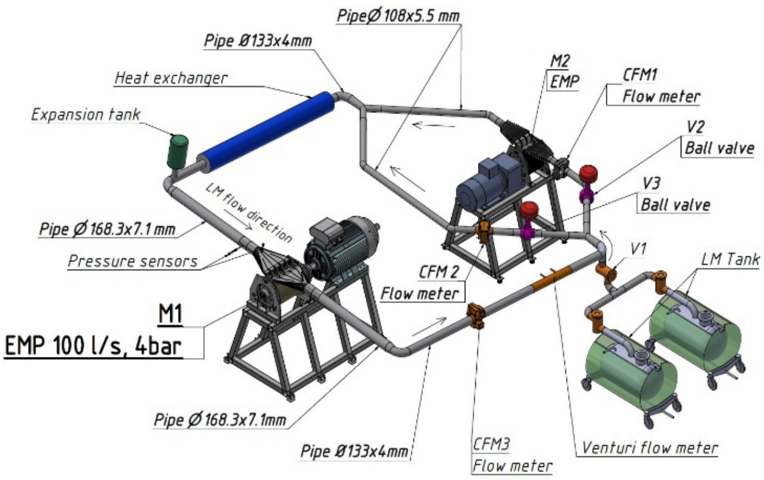

Figure 7. EMP prototype integrated into the Sodium Loop facility (Institute of Physics of University of Latvia liquid metal Laboratory).

The experimental campaigns were carried out in stages. Initial tests with a 60 L/s EMP investigated coast-down behaviour using flywheels of different inertias, supported by loop upgrades to reproduce realistic pressure drops (Fig.8).

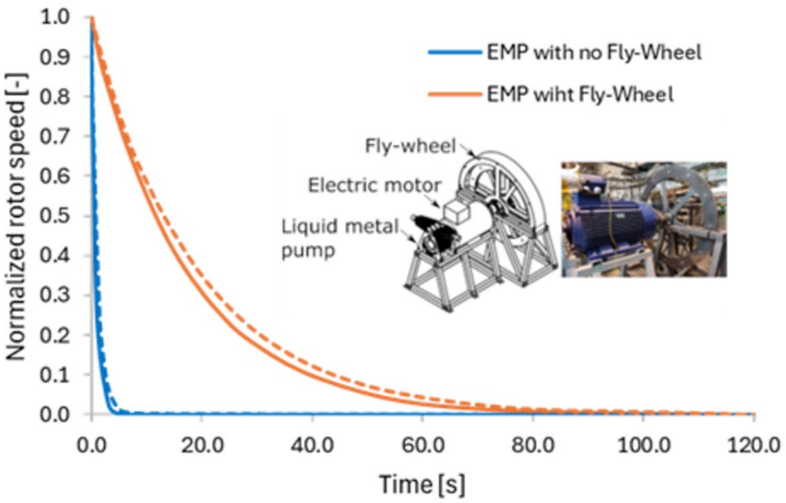

Figure 8. Predicted and measured time dependence of rotor's angular speed of the EMP after shutting down of the electric motor (coast-down): experiment (solid-line); theory (dash line). [8]

Subsequent experiments pushed the pump to maximum flow rates, analyzing EMP–loop interaction and transient performance. A 100 L/s EMP prototype was then designed, manufactured and tested in sodium, to define operating pressure-flowrate (P–Q) curve (see Fig. 9) and coast-down curves. The results were extrapolated to lithium. Complementary studies measured hydraulic resistance, component losses, and inlet pressure distribution to avoid cavitation, with data compared to 3D simulations. Together, these campaigns provide the operating characteristics and validation of EMP design and performance.

Last phase, currently under development, focused on the operation of the pump under very low inlet pressure [9], simulating the DONES conditions, where the loop is connected to the vacuum of the accelerator and the hydrostatic lithium column feed up the pump inlet. These experiments push the pump until the cavitation to establish the operational limits. Preliminary results confirm the numerical simulations, where cavitation risk appears at about 0.3 bar (absolute pressure). Additional optimization features are being developed to push this limit even lower.

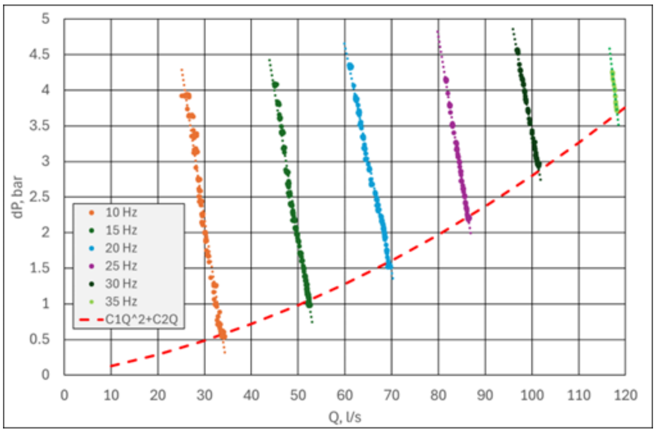

Figure 9. Experimental measurement of the pressure (dP) and flowrate (Q) curve of the EMP for different inverter frequencies of the electric motor. Red dashed curve represents loop hydraulic resistance.

4. THE DONES EXPERIMENTAL PROGRAMME

The IFMIF-DONES facility will provide a fusion-like neutron source incurring damage rates of 50 dpa in less than 3 full power years (fpy) applicable to a 0.1-liter volume, and 20 dpa in less than 2.5 fpy applicable to a 0.3-liter volume, with temperatures ranging between 250 and 550ºC in the high flux region [10]. Such a high neutron flux will allow to develop a database of fusion-like neutron irradiation effects in the fusion-power reactor materials represented by miniaturized specimens and simultaneous irradiation modules. Complementary experiments using high-flux neutrons are also planned beyond materials irradiation in areas such as nuclear physics, radioisotope production, medicine or industrial applications. IFMIF-DONES will present flexibility features of the beam footprint dimensions and the configuration of the irradiation modules to balance the needs of the users between the required volume and the type of experiments needed to perform, to allow for the the widest range of possible experiments in the facility.

Fusion experiments

As mentioned above, the main mission of DONES Programme is to perform a database of the behaviour of materials under fusion-like conditions for the design, licensing and safe operation of a fusion demonstration power reactor (DEMO) and set up database for benchmarking of radiation responses of materials. The most irradiated module of the facility will be the High Flux Test Module (HFTM), located at 2mm from the liquid lithium curtain and therefore, experiencing the highest damage rate for the materials. Here, 32 capsules of small sample specimens (Small Specimen Test Techniques, SSTT), containing between 80 and 120 SSTT for capsule will be irradiated at neutron full power [11].

One of the principal experiments using SSTT capsules in DONES will be the irradiation testing, and the licensing of Reduced Activation Ferritic-Martensitic steels (RAFM), in particular EUROFER97 and F82H, two of the most promising materials to form the first wall of DEMO and the future fusion reactors.

Besides structural materials such as RAFM steels, DONES will be used for the irradiation and qualification of functional materials such as tungsten and copper alloys, used for first wall and divertor heat-sink (e.g., CuCrZr). In addition, tests of optical and electronic/di-electric components such as insulators, superconducting materials, diagnostics, transmission and radiofrequency materials, and reflectors can be performed at DONES.

The facility includes further capabilities for experimental campaigns related to other remaining fusion challenges, one of the most important being tritium production and extraction techniques better known as the Breeding Blanket (BB) technologies. There are four breeding blanket concepts in the European fusion roadmap including Water-cooled Lead-Lithium (WCLL), Helium-Cooled Lead-Lithium (HCLL), Dual- Coolant Lead-Lithium (DCLL), all of them based on liquid metal technologies and Helium-Cooled Pebble Bed (HCPB), which is based on solid breeding. For this purpose, a mock-up called BLUME (BLanket fUnctional Materials modulE) is being designed for the testing and validation of functional materials, heat transfer experiments, neutronics validations, tritium transport behaviours and breeder/structure thermo-mechanical interactions at DONES facility. Figure. 10 depicts the first approach to the experimental programme.

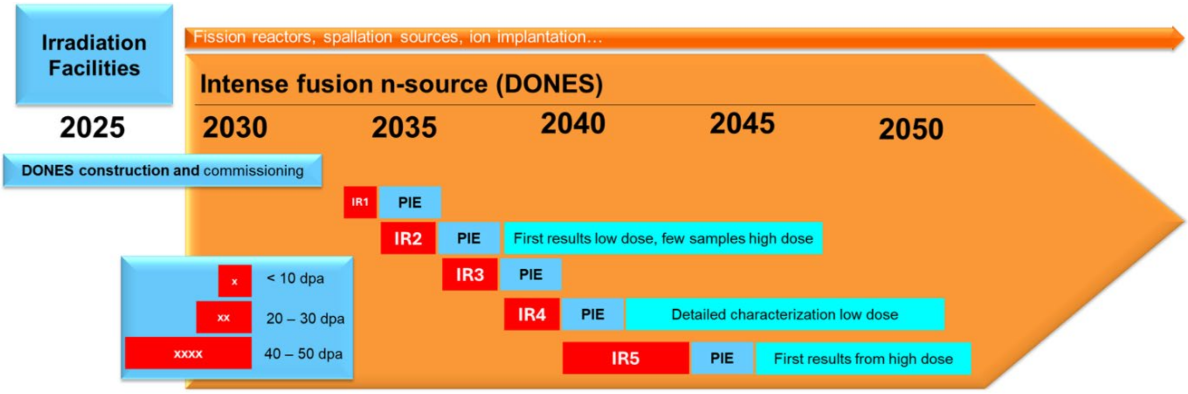

Fig. 10. First approach to the experimental programme

Non-fusion experiments

IFMIF-DONES will also be used for complementary experiments [12] which will make it the most unique multidisciplinary neutron facility. Some experiments will require high flux of neutrons and therefore will be performed in the high flux area, depending on the irradiation campaign. However, the most part of complementary experiments do not require such a huge neutron flux and therefore, will be performed in the medium to low flux regions.

On the one hand, neutrons traversing the HFTM will be collimated and used outside the test cell, for producing continuous collimated neutron beam that will reach an intensity of 1.5×10^{11} n/cm2/s with a beam footprint of about 8 cm diameter. A broad range of experiments can be performed with fast neutrons such as neutron imaging experiments, elemental composition studies of biological materials, study of neutrons-nucleus interactions, testing of superconductors, study of antimatter and neutrinos, or the production of the ^{99}Mo radioisotope for medical applications. With thermal or cold neutrons it is possible to perform experiments such as neutron scattering, neutron diffraction, to measure of the neutron-antineutron oscillation or neutron radiography for industrial and scientific applications. Also, the production of radioisotopes for cancer treatment (e.g., ^{85}Kr) can be performed with cold neutrons.

On the other hand, the extraction of ~0.1% of the deuteron beam from the accelerator beamline before reaching the liquid lithium target could be a potential way of further extending the capabilities of DONES for other relevant experiments. Pulses of deuterons would be extracted by means of a kicker and directed on to the floor below the accelerator. In this area, experiments with pulsed deuterons or pulsed neutron beams produced by deuteron-induced reactions on a secondary target could be performed. Most promising of these require the implementation of the neutron time-of-flight (n-TOF) technique.

Neutron time-of-flight (n-TOF) facilities are among the most versatile systems for measuring energy-dependent neutron-induced reaction cross sections and secondary particle emissions. In these setups, pulsed neutron beams travel along a well-defined flight path and interact with the samples at specific time intervals, enabling the determination of the neutron velocity based on their time of flight. A time-of-flight installation at DONES could cover a large variety of cross section measurements and nuclear structure experiments required for nuclear technologies (fusion and fission), nuclear astrophysics, particle and astro-particle physics. In addition, the pulsed neutron beams could be used for inducing fission and performing nuclear structure studies on the resulting fission fragments, by coupling advanced γ-ray detection setups to a high-resolution magnetic spectrometer. The pulsed deuteron beam could also be used directly for producing valuable (d,x) reaction data for a broad range of applications, including fusion.

5. REFERENCES

[1] W. KRÓLAS et al "The IFMIF-DONES fusion oriented neutron source: evolution of the design", Nucl. Fusion 61 (2021) 125002

[2] A. IBARRA, et al. "The European Approach to the Fusion-like Neutron Source: The IFMIF-DONES Project", Nucl. Fusion 59 (2019) 065002

[3] A. IBARRA et al. "DONES performance, experimental capabilities and perspectives", Nucl. Fusion 65 (2025) 122006. Special Issue on the IFMIF-DONES Fusion Neutron Source.

[4] S. KWON et al. "High beam current operation with beam diagnostics at LIPAc" Journal of Instrumentation, Volume 19, (2024) T05013

[5] C. TORREGROSA-MARTIN et al. "Safety engineering approach and licensing strategy of IFMIF-DONES". Accepted manuscript. IOP Publishing Ltd on behalf of the IAEA DOI 10.1088/1741-4326/adee2f

[6] A. SABOGAL et al, "MuVacAS: Experimental Setup for testing Mitigation Strategies against Loss of Vacuum Accidents in the IFMIF-DONES Accelerator", Fusion Engineering Design, (2025) 115473

[7] G. GALLARDO et al. "Virtual sensors using neural operators applied to facilities with extreme conditions", Spanish National Congress on R&D in Defense and Security (DESEi+d 2024).

[8] F.S. NITTI et al. "The lithium systems of the IFMIF-DONES facility", Nucl. Fusion 65 (2025) 122004

[9] A. BRĒĶIS et al. "Electromagnetic pump with rotating permanent magnets operation at low inlet pressures", Fusion Engineering and Design, Volume 194, 2023, 113919,

[10] Y. QIU et al. "Overview of recent advancements in IFMIF-DONES neutronics activities". Fusion Engineering and Design, 201, (2024) 114242.

[11] F. ARBEITER et al. "The IFMIF-DONES Irradiation Modules". Nucl. Fusion 65 (2025).

[12] M. LEWITOWICZ, et al. White book on the complementary scientific programme at IFMIF-DONES. Institute of Nuclear Physics Polish Academy of Sciences. (2016) ISBN 978-83-63542-68-9

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion) and within the framework of the DONES-ConP1 Consortium, funded by the European Union via the Euratom Research and Training Programme - Euratom Work Programme 2023-2025 for nuclear research and training under Grant Agreement No 101145952 — DONES-ConP1. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. In addition, it has been co-financed by the Government of Spain, the Junta de Andalucía and the European Regional Development Fund (ERDF) and by the Consejo de Seguridad Nuclear, Spain, (SUBV12/2021 Ref. PR-051- 202), has been co-financed by the Polish Ministry of Education and Science in the framework of the International Co-financed Projects (PMW) programme, and financed by HI IBERIA under the DONES-FLUX project, (MIP-20221017-Misiones CDTI-2022), supported by the Ministry of Science and Innovation of Spain. It has also been performed with the support of L. Buligins, J. Maestre, A. Sabogal, L. Monasterio, the DONES On-site Joint Team, the DONES ConP1 team, the EUROfusion WPENS team and the DONES Users Community.