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Deliverable 4.6:

Report on the possibilities opened for nuclear materials by the ESFRII roadmap for nuclear infrastructures

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List of abbreviations

AISBL	International non-profit Association
DONES	DEMO Oriented NEutron Source
EC	European Commission
ESFRI	European Strategy Forum on Research Infrastructures
ESNII	European Sustainable Nuclear Industrial Initiative
EU	European Union
FPF	Full Power Facility
FTS	Fusion Target Station
HFTM	High Flux Test Module
IFMIF	International Fusion Materials Irradiation Facility
IPS	In-Pile Section
JHR	Jules Horowitz Reactor
LBE	Lead-Bismuth Eutectic
MTR	Materials Test Reactor
MOX	Mixed Oxide fuel
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NuPECC	Nuclear Physics European Collaboration Committee
ORIENT NM	Organisation of the European Research Community on Nuclear Materials
PIE	Post Irradiation Examination
R&D	Research & Development
SET	Strategic Energy Technology Plan
SRA	Strategic Research Agenda

ESFRI Roadmap for nuclear infrastructures

This report is part of the deliverables for Task 4.5 Interaction of the EJP with infrastructure and facilities.

In the ESFRI 2021 roadmap (fusion and fission) there have been recognized three projects as the ones that could open the possibilities for nuclear materials research and testing: IFMIF-DONES, JHR, and MYRRHA.

Materials for commercial fusion reactors will require qualification. A fusion reactor requires materials to be exposed to high fluence with fast spectrum and dedicated helium production to mimic fusion operational conditions. Within the Broader Approach agreement, commissioning of the first components of the neutron source prototype IFMIF-EVEDA LIPAc installed in Rokkasho, Japan, is under way. The EUROfusion programme supports IFMIF and proposes the ESFRI Project IFMIF-DONES as an interim step. Therefore, the fusion program is based on an international collaboration and competition, involving several countries outside of the EU, and is based on a solid roadmap with well-defined objectives.

Nuclear fission plays an important role to provide a stable electricity production in the EU. In the field of Accelerator Driven Systems which could be used for transmutation of long-lived actinides, a staged approach was adopted by MYRRHA, leading to the full realization of the facility by 2036. While recognizing the high scientific value of the project, the Forum decided not to award to MYRRHA the status of Landmark in 2021, expecting in the next few years a stronger case for implementation, especially since the creation of an AISBL – International non-profit Association under Belgian Law – in September 2021.

JHR will not be discussed as it has already been extensively covered by the Report on Deliverable 4.5 (Availability and future plans of MTRs and consistency with JHR roadmap).

IFMIF-DONES

The main requirement for this neutron source is to produce fusion characteristic neutron spectrum with enough intensity to allow accelerated testing, up to a level above the expected operational lifetime, with an irradiation volume large enough to allow the characterization of the macroscopic properties of the materials of interest required for the engineering design of DEMO and the future fusion Power Plant.

IFMIF (International Fusion Material Irradiation Facility) can achieve all these targets using two 40 MeV deuteron linear accelerators, each delivering a 125 mA beam current with 100% duty cycle. Both beams strike a liquid lithium jet as a target, thus providing an intense neutron flux density of about 10^{18} n/m^{2}s with a broad energy peak near 14 MeV. DONES (Demo-Oriented Neutron Source) is conceived as a simplification of IFMIF with the idea to accelerate its implementation able to provide as soon as possible the materials information required for the design and construction of DEMO. The main simplifications consist on:

- reduction to only one accelerator line, resulting in a neutron flux of 50% compared to IFMIF;
- use of the irradiation area only for irradiation of structural materials (and not for in beam experiments), reducing the technological complexity to assure enough availability for DEMO design and ;
- elimination of Post Irradiation Examination laboratories, relying on specific facilities elsewhere.

DONES design includes though its future upgrade to a complete IFMIF including two accelerator lines.

IFMIF-DONES Irradiation module

The projected neutron flux, produced by one deuteron beam of 125 mA striking on a lithium target with a footprint of 200 x 50 mm^2, is sufficient to create a damage rate higher than 10 dpa/fpy in a volume of approximately 0.5 litre. The High Flux Test Module (HFTM) is the dedicated assembly to bring material SSTT specimens into the high neutron flux region of the neutron source and maintain the specified irradiation conditions. The material specimens are destined for Post Irradiation Examination (PIE) – for example mechanical or micro-structural testing – after an irradiation period of several months. The irradiation conditions are specified by neutron flux, neutron energy spectrum and temperature – as well as the spatial and temporal variations of these quantities.

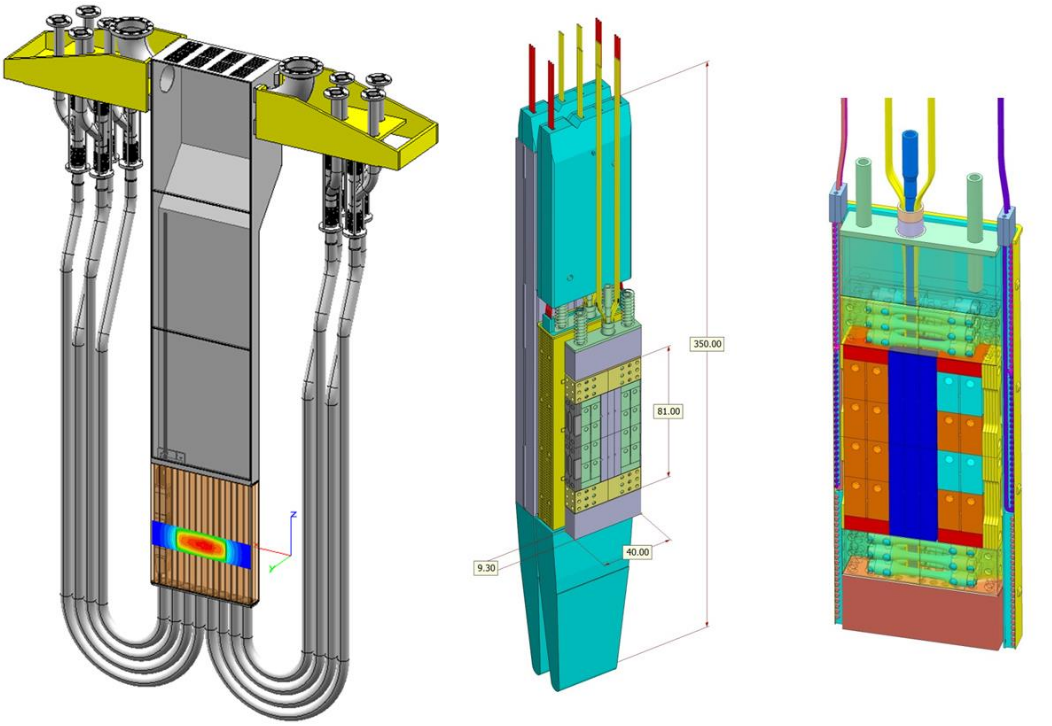
The HFTM should provide precise adherence to the specified irradiation conditions for DEMO design needs and should maximize the irradiation performance, expressed as the product of irradiated specimen volume and the received neutron fluence. The HFTM is designed to be mainly dedicated to the research on RAFM steels, to be tested in the temperature range 250-550°C, with an option to provide irradiation up to 650°C. The uncertainty of temperature for 80% of the specimen is demanded to be below +/-3% related to the absolute nominal temperature. Further, it is an aim to cool the specimen from their temperature to below 200°C to freeze the irradiation defects after the irradiation within 15 minutes.

The design of the HFTM has been evolving for the latest five years in part to optimize the irradiation volume available. According to the design provided in the IFMIF/EVEDA phase, where several irradiation modules were planned, the HFTM is built from a thin walled container divided into eight compartments, into which three can be placed in each. A total number of 24 capsules may be placed in the container 8x3 (~ 74 mm thickness in beam direction, three capsules in a row). Along the simplification of the plant down to the DONES concept where only the HFTM will be installed, several options were analyzed. One option was to enlarge the module to be able to host four rows of rigs in a 8x4 container. Another alternative was to install two identical HFTM with the primitive design.

The central four compartments (360 cm^3 for specimens in the 24-rig model) are inside the beam footprint where neutron flux levels are suitable for high quality irradiation experiments. The remaining four out-of-centre compartments are also filled with rigs. The function of these so called companion rigs is mainly to act as lateral neutron reflectors, but also to accommodate instrumentation, like fission chambers for online flux monitoring. In the two compartments located at the lateral ends most distant from the source, the neutron flux amounts to only about 10% of the central positions, but flux gradients are low, and can thus be attractive as additional irradiation space.

The arrangement of the specimens in the HFTM is adapted to the beam footprint of the neutron source, which is 20 cm x 5 cm. The specimen alignment, and the dimensioning of reflectors, must limit the neutron flux gradient to less than 10% of the individual sample gauge volume. In order to transmit the neutron flux with as little as possible losses to the specimens, the HFTM structures are designed as thin as achievable, and avoid materials with a high neutron absorption cross section.

The specimens are contained in rectangular irradiation capsules equipped with electrical heaters, which can partly compensate the spatial distribution as well as temporal fluctuations of the nuclear heat release. In order to homogenize the temperature field, gaps between the specimens are to be filled up with liquid Na.



HFTM Assembly

Packet of 3 Rigs

Cut-open capsule with specimens

Figure 1 HTFM assembly preview

Capsule description

The HFTM Irradiation Capsule Assembly is the central part of the HFTM. The capsules contain the material specimens, the scientific payload of the HFTM. It is a prismatic body with a rectangular cross section. The current capsule design has a theoretical specimen-stack-volume of 44.4 cm and an expansion volume of approximately 10 cm^3 in the Irradiation Capsule Closer Assembly. The outer dimensions of the capsules including the Insulation-Gap Spacers are 22.3 mm in beam direction (thickness, in local y-direction), 51.3 mm width (local x-direction) and 120.0 mm height (local z-direction).

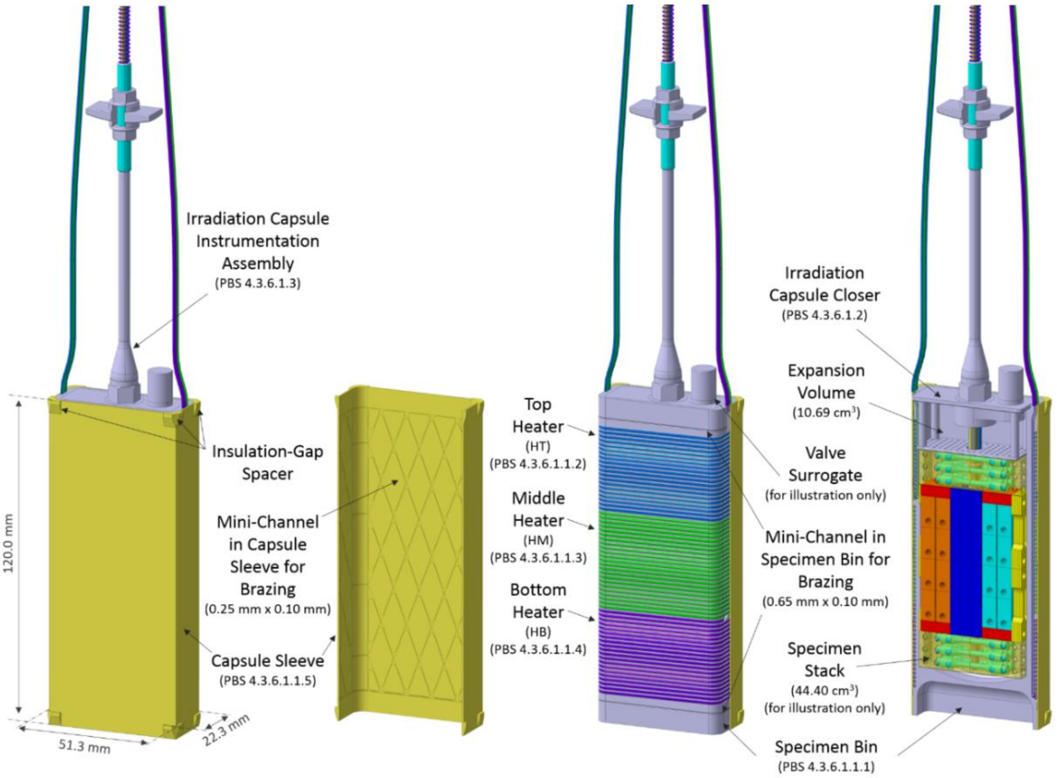


Figure 2 HFTM Capsule preview

Description of neutronics in the HFTM volume

Although the nominal deuteron beam footprint is a rectangle 20 cm x 5 cm, the high Energy beam Transport in the accelerator will be able to change the footprint shape to smaller size. In there is a description of the neutronics expected in the DONES plant depending on the several possible beam footprint configuration. The double HFTM configuration was assumed in this analysis. Neutron fluence rate [n/cm^2s] mesh-tally horizontal section in the central part of the HFTM is shown in Figure 1Figure 3. The geometry of the 24 rigs of each irradiation module is overlapped on the picture. Regarding the first HFTM, in the most area comprised by the 12 central rigs, the neutron fluence rate observed is from 7E14 to 1E14 n/cm^2s, while, in HFTM2 central area (12 central rigs) the neutron fluence rate is between 2E14 and 5E13 n/cm^2s.

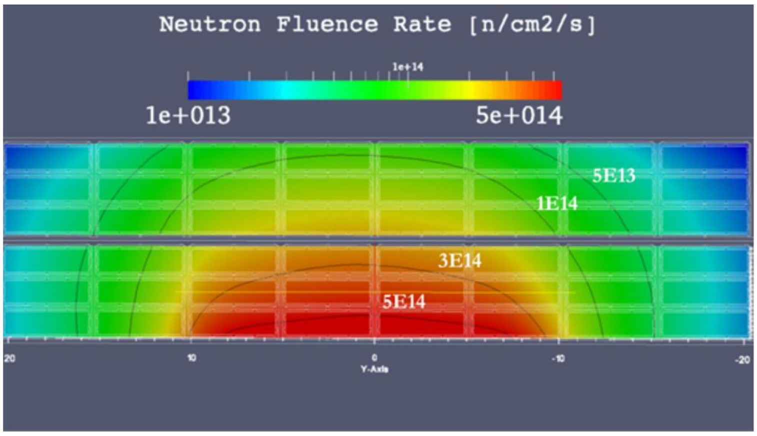


Figure 3 Neutron fluence rate expected for the nominal case

Higher neutron fluence, and therefore a higher damage rate, may be obtained with a more concentrated beam footprint shape. The disadvantage would be a reduction of the available volume where the the desired damage rate is achieved. The volume in the HFTM or HFTM2 where the damage dose rate(dpa/fpy) is above a given value is plotted in Figure 4 for several beam configurations. A damage dose rate up to 50 dpa is achievable.

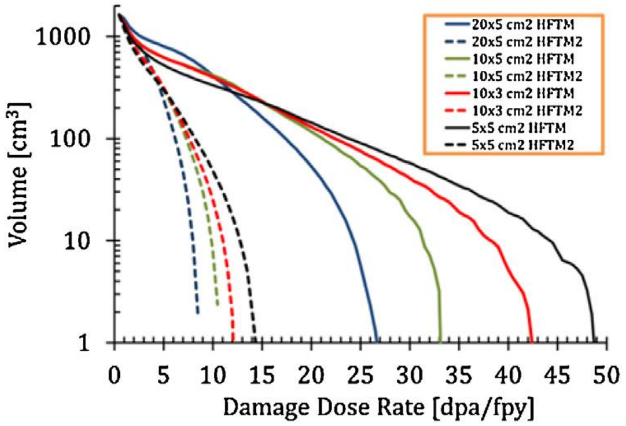


Figure 4 The volume where the damage dose rate is above a given value

MYRRHA

In the framework of the European Sustainable Nuclear Industrial Initiative (ESNII), a R&D platform aiming to demonstrate Generation-IV Fast Neutron Reactor technologies, MYRRHA has been identified in 2010 as a major facility contributing to the EU's Strategic Energy Technology Plan (SET plan). Also the Nuclear Physics European Collaboration Committee (NuPECC), whose aim is to promote collaborative ventures between nuclear physicists within Europe, has selected ISOL@MYRRHA to be part of its long-range plan of the top facilities for nuclear physics in Europe.

MYRRHA is designed as a flexible fast spectrum irradiation facility. This means that a fast neutron spectrum is present at every location in the reactor and that every fuel assembly position can be loaded with a driver MOX fuel assembly, a minor actinides fuel experimental assembly, a dedicated experimental rig for material irradiation or medical and industrial radioisotopes production rig. In this way, the entire reactor volume offers possibilities of loading experimental fuel assemblies in conditions similar to the reactor conditions, being a fast neutron spectrum, and in contact with the flowing liquid lead-bismuth at reactor operating temperatures. MYRRHA will also be able to host at least 8 in-pile sections (IPS) (representing a total volume of 8 x 3.700 cm3) with a core-loading pattern optimized to obtain the most appropriate irradiation conditions in the IPS. In this double-walled IPS, a different coolant (Na, NaK, He, H_2O) can be present with temperature and pressure conditions optimized for the experimental fuel/material loaded in the IPS. The R&D program supporting the design of MYRRHA aims at validating solutions on the main design challenges: lead-bismuth liquid metal in reactor conditions, MOX fuel qualification, materials qualification, resilience of innovative components, reactor physics and modelling of fast and sub-critical cores.

The MYRRHA Preparatory Phase was successfully completed in 2016. The MYRRHA implementation plan involves three phases:

- **Phase 1**: design and construction of the first linac section (up to 100 MeV).
  This phase will confirm the linac's operational reliability required later to drive the reactor with the 600 MeV proton beam. In addition, it consists of the Proton Target Facility for the production of medical radioisotopes and for fundamental and applied research in physics as well as for material research. The third component is the Fusion Target Station, where materials for fusion reactors will be tested. The first phase also includes research and development of the linac extension to 600 MeV and of the sub-critical reactor. Finally, reactor pre-licensing is also part of Phase 1. This phase is scheduled for completion in 2026.
- **Phase 2**: extension of the 100 MeV linac to 600 MeV.
  This extension is required to drive the reactor. When completed, the linac will be approximately 400 m long. Phase 2 is scheduled for completion in 2033.
- **Phase 3**: construction of the reactor

> The double wall, unpressurised pool-type vessel will accommodate all primary systems. The sub-critical reactor will be fed by neutrons that are generated by the spallation source that, in turn, is fed with protons from the linac. This fast reactor is cooled by lead-bismuth eutectic (LBE) and has a maximum thermal power output of 100 MW. The reactor is scheduled to be commissioned in 2036.

A legal entity for the construction, the operation and the decommissioning of MYRRHA was identified. The plan is to set up MYRRHA as an AISBL under Belgian law. Important aspects such as the appropriate rules concerning nuclear liability and contractual liability of the MYRRHA consortium and its members were analyzed in detail and included in an Intergovernmental Agreement document.

MYRRHA Full Power Facility

The Full Power Facility (FPF) is a flexible research infrastructure designed to handle a proton beam of 4 mA and 100 MeV. The FTS consists of a flowing water containment separated from the vacuum by means of a thin metal window. By adjusting the position in the water tank, the proton beam energy can be fine-tuned to match irradiation conditions required to investigate fusion materials. The design will also enable the introduction of a water cooled spallation source that can generate a hybrid proton-neutron irradiation field. In this water-filled containment, FTS users can further design irradiation experiments within a predefined safety envelope.

The following elements will comprise the FPF:

- an irradiation module
- an instrumentation module
- a hot cell for transportation and sample reloading
- a dedicated testing laboratory in hot cells of Nuclear Material Science Institute.

Upon operational deployment, the FPF will be applied to investigate accumulated irradiation damage and/or to perform in-situ testing of materials exposed simultaneously to mechanical load and irradiation beam. Irradiated samples will be transferred to hot cell facilities at SCK CEN or elsewhere, where they can be thoroughly examined with state-of-art equipment. FPF exploitation focus will therefore be on screening perspective/innovative materials and assessment of irradiation-creep softening effects as well as diagnostic equipment validation.

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