Overview of the IFMIF/EVEDA Project

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Abstract. IFMIF, the International Fusion Materials Irradiation Facility, presently in its Engineering Validation and Engineering Design Activities (EVEDA) phase under the Broader Approach Agreement, will allow accelerated testing of structural materials with fusion relevant neutrons at >20 dpa/year in 500cm^3.

IFMIF consists of two 125 mA and 40 MeV D+ linear accelerators operating in CW mode. The parallel beam lines impact on a liquid lithium target with a 200mm x 50mm beam cross section. The target consists of a 25mm ±1 mm thick liquid lithium screen flowing at 15 m/s and 250 °C channelled by a R250mm concave RAFM backplate. The suitable neutron flux generated in the forward direction will irradiate 12 test capsules housing around 1000 small specimens independently cooled with helium gas to allow wished temperature during irradiation.

The Engineering Design Activity (EDA) phase of IFMIF was successfully accomplished within the allocated time.

The Engineering Validation Activity (EVA) phase has focused on validating the Accelerator Facility, the Target Facility and the Test Facility with the construction of various prototypes. The EVEDA Lithium Test Loop (ELTL) has successfully demonstrated the long term stability of a lithium flow under IFMIF nominal operational conditions with 25 days continuous operation in Oarai (JAEA) at 250°C and 15 m/s within ±1 mm free surface fluctuations. A full-scale prototype of the High Flux Test Module has been successfully tested in the HELOKA loop (KIT Karlsruhe) demonstrating the feasibility of the uniformity in the temperature selected for the specimen set irradiated in each capsule. LIPAc, presently under installation and commissioning, will validate the concept of IFMIF Accelerators with a D+ beam of 125 mA and 9 MeV. The final phases of the commissioning of the H+/D+ beams in Rokkasho Fusion Institute at 100 keV has taken place during 2016; the commissioning of the 5 MeV beam is to follow during 2017. The 9 MeV D+ beam through the superconducting cryomodule assembled in Rokkasho will be achieved with this decade.

The realisation of a fusion relevant neutron source is a necessary step for the successful development of fusion. The stable progress achieved in this final EVEDA phase is ruling out technical concerns and potential showstoppers raised in the past.

In the light of costs, which are unquestionably marginal to those of a fusion plant, a situation has emerged where soon steps towards constructing a Li(d,xn) fusion relevant neutron source could be taken.

The future paper to be published in Nuclear Fusion will develop extensively the aforementioned points, that are not properly detailed in this pre-print due to the limited allowed space.

1. Fusion relevant neutron sources: essential missing step in fusion materials research

The technological challenges of fusion energy are intimately linked with the availability of suitable materials capable of reliably performing under the unrivalled severe operational conditions of fusion reactors. The hard monoenergetic spectrum associated with the deuterium-tritium fusion neutrons (14.1 MeV compared with <2 MeV in average for fission neutrons) will release significant amounts of hydrogen and helium as transmutation products that might lead to a presently undetermined degradation of structural materials after few years of operation. Fission and fusion materials world exhibit growingly common points, synergies between Generation IV fission reactors and fusion reactors are more obvious than never; however, fusion materials research needs are broader than fission ones.

Fission materials have always been tested in experimental fission reactors. While a fission reactor can be sized down, a fusion reactor presents certain size and complexity limitations, which tend to correlate with cost. Hundreds of experimental fission reactors are available worldwide, unfortunately an equivalent facility to cope with fusion materials research with suitable flux and neutron spectrum does not exist; even if we knew how to maintain stable fusion reactions, it would face unsolved structural materials problems.

Degradation of materials under neutron irradiation was already anticipated in 1946 by Eugene Wigner, who argued theoretically that neutrons could displace atoms through irradiation: *The matter has great scientific interest because pile irradiations should permit the artificial formation of displacements in definite numbers and a study of the effect of these on thermal and electrical conductivity, tensile strength, ductility, etc., as demanded by the theory*. Nuclear fusion materials research started in the early 1970s, one decade after the first commercial fission reactors started operation, following the observation of the degradation of the irradiated materials. For a fusion reactor, strict safety standards are required for the thermomechanical properties of the in-vessel components that are exposed to severe irradiation and heat fluxes; they are also an essential requirement for the economic viability of fusion. Furthermore, not only the radiation hardness of components has a strong impact on the long-term operation of a plant, but also the operating temperature of the materials involved determines the thermodynamic efficiency of power plants of the future.

Damage of materials induced by radiation under a given neutron spectra and fluxes is measured by the Norgert-Robinson-Torrens displacement per atom ($\mathrm{dpa_{NRT}}$) unitless quantity, that incorporates to a first approximation, the dependence of the response of the material under irradiation of the neutron energy. In the case of inelastic reactions, a significant part of the neutron energy is transferred to the recoiling atom, which remains in an excited state. Typically, incident neutrons must have energies above a sharp threshold, thus both the neutron and the PKA excited nucleus end up having a substantially lower kinetic energy. Neutron-induced transmutations are as important as displacement damage in determining the suitability of a given material for nuclear applications. In fusion reactors, the 14.1 MeV neutrons will lead to a helium production ratio of around 12 appm/dpa, mainly through $^{56}\mathrm{Fe}(n,\alpha)^{53}\mathrm{Cr}$ reactions (in fission reactors, this ratio is 0.3 appm/dpa, owing to the 3.7 MeV threshold of the reaction). The accumulation of helium leads to a significant mechanical impact even with low concentrations; helium-induced embrittlement, observed in fission reactors, is a major concern for fusion materials. Conversely, the high permeation of hydrogen, mainly generated through $^{56}\mathrm{Fe}(n,p)^{56}\mathrm{Mn}$ reactions at a rate of 45 appm/dpa, makes the potential degrading impact of hydrogen less relevant, although a combined detrimental enhancement of both helium and hydrogen is expected. In turn, spallation sources produce a neutron spectrum with long tails, reaching the energy of the colliding protons (nowadays in the order of GeV), that generate light ions as transmutation products that induce measurable changes of alloying properties and typically 70 appm He/dpa ratio in average with difficult control of temperature gradients during irradiation [1]. See figure 1 to understand graphically this critical point.

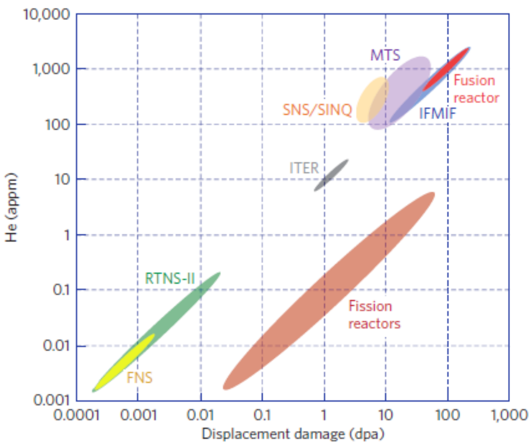

Figure 1 Graph showing the correlation of dpa versus appm of he generated for the different existing possibilities of testing materials (alternative and IFMIF) compared with fusion reactor conditions

The safe design of a fusion power reactor is indispensable for getting the operational license granted by the corresponding Nuclear Regulatory Agency. Overcoming the historical lack of a fusion relevant neutron source for materials testing is an indispensable pending step in fusion roadmaps. The neutron flux, its spectrum and the temperature under irradiation are essential parameters to learn the behaviour of structural materials exposed to the severe conditions in a fusion reactor after ITER, where potentially structural damage exceeding 15 dpa_{NRT} per year of operation [2] is expected compared with less than 3 dpa_{NRT} of the latter.

2. The IFMIF/EVEDA project

An assessment of possible solutions for a neutron source suitable for fusion materials testing concluded in the early 70s that Serber's deuteron stripping reactions [3] in liquid lithium would be the best possible candidate. The seminal proposal towards a fusion relevant neutron source based on Li(d,xn) nuclear reactions was published in 1976 [4] and as early as 1979, the first review of the state-of-the-art of the underlying technology concluded that such a neutron source is indispensable to validate and calibrate the existing models [5]. The diversity of key parameters (neutron flux, spectrum, fluence, material temperature, mechanical loading conditions, microstructure, thermo-mechanical processing history, lattice kinetics…) can only be found out unambiguously by experiments with fusion relevant neutron sources. Thus a neutron source with suitable flux and spectrum becomes an unavoidably step to design and construct any fusion reactor device subsequent to ITER. The technical challenges were enormous since such a facility required an accelerator to perform in unprecedented conditions of beam power, a lithium loop running in a stable manner under severe specifications of stability, irradiation capsules capable to withstand the strong irradiation and house reliable small specimens and precise remote handling equipment to yearly replace lithium channelling equipment in the beam impacting area and capsules. The technical challenges lead to explore alternative ideas, beyond the exoticism of some of the proposals, all presented serious technical flaws and the international consensus on the suitability of Li(d,xn) was systematically achieved. The genealogy of a Li(d,xn) fusion relevant neutron source has already been detailed elsewhere [6].

Since 1994, the "International Fusion Materials Irradiation Facility" (IFMIF) is the reference concept within the Fusion community. The IFMIF/EVEDA project (acronym that stands for

Engineering Validation and Engineering Design Activities) is one of 3 projects defined in the Broader Approach Agreement between Japan and EURATOM, which entered into force in June 2007. The IFMIF/EVEDA specific Annex in the BA Agreement mandates the project to produce an integrated engineering design of IFMIF and the data necessary for future decisions on the construction, operation, exploitation and decommissioning of IFMIF, and to validate continuous and stable operation of each IFMIF subsystem. Thus, IFMIF/EVEDA project consist on two parallel mandates: the EDA [6] and the EVA [7].

2.1 EDA, the Engineering Design Activities

IFMIF will generate a neutron flux with a broad peak at 14 MeV thanks to two parallel 125 mA CW deuteron accelerators at 40 MeV colliding with a footprint of 200 mm x 50 mm in a liquid lithium screen. The lithium target will be flowing at 15 m/s with a stable thickness of 25 +/-1 mm to fully absorb and evacuate the 2 x 5 MW beam power. The 40 MeV energy of the beam and the 2 x 125 mA current of the parallel accelerators have been tuned to reach a comparable neutron flux (10^{18} $m^{-2}s^{-1}$) to the one expected in the most exposed structural materials of a fusion power reactor. An irradiation volume of 500 cm^3 will contain 12 independently cooled capsules housing each around 2 x 40 small specimens for a total of around 1000 specimens. Each capsule can be independently cooled at a target temperature ranging 250 °C $< T <$ 550 °C with the specimens presenting a $\Delta T < 3\%$ during irradiation. The neutron flux provided and the design of its High Flux Test Module containing the 12 capsules directly irradiated allows >20 dpa per year of operation at fusion relevant conditions. The Test Cell is designed to also house a Middle and a Low Flux test Module for higher volumes but lower dpa capabilities. IFMIF is conceived for 30 years of operation.

The IFMIF plant is composed of 5 specific facilities. Accordingly, the systems designed for the IFMIF plant are grouped into the Accelerator Facility (AF), the Lithium Target Facility (LF), the Test Facility (TF), the Post Irradiation Examination Facility (PIEF) and, the Conventional Facilities (CF). The latter group of systems ensure power, cooling, ventilation, rooms and services to the other facilities and itself. An eye view of the IFMIF facility is available in Figure 2.

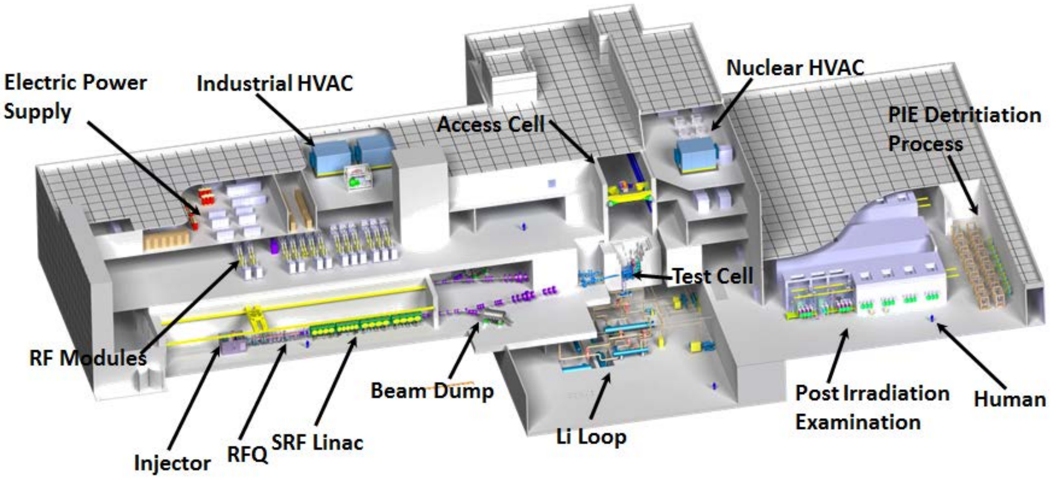

Figure 2. Artistic bird's eye view of the IFMIF's Main Building.

The accomplishment of the EDA phase in June 2013 exactly within the six years allocated, is intimately linked with the present findings obtained by the validation activities, which albeit on-going at the time of the release of the report, allowed the definition of the design to be consolidated by the construction and operation of prototypes [6,7]. The report released is composed of five major elements: (1) the ‘executive summary’; (2) the ‘IFMIF plant design description’ (PDD), that summarises the content of the more than 100 technical reports; (3) a careful cost and schedule report, based on the experience gained with the construction of prototypes during the EVA phase and the analysis of recognised Japanese and European engineering companies; (4) annexes to the PDD; and (5) 34 detailed design description documents (DDDs) of all the sub-systems supporting the PDD. A list of all the documents generated is available in Figure 3. The first two documents listed below, the Executive Summary and the IFMIF Plant Design Description Document (PDD) have been widely distributed in a handy booklet.

In the future paper to be published in Nuclear Fusion further details of the engineering design will be addressed.

Executive Summary (this document)

IFMIF Plant Design Description Document (PDD)

Cost Estimate Report

PDD Annexes

- **I. Design Guidelines**
  - Annex I.1-CAD Guidelines
  - Annex I.2- EDA ALARA Process Guideline
  - Annex I.3- Fire Protection Guideline
  - Annex I.4- Hazard Evaluation Guideline
  - Annex I.5- Human Factor Approach Design Guideline
  - Annex I.6- IFMIF Generic Site Assumptions Guideline
  - Annex I.7- IFMIF Materials Library
  - Annex I.8- Liquid Metal Handling Guideline
  - Annex I.9- RAM Guidelines
  - Annex I.10- Remote Handling Design Guideline
  - Annex I.11- Safety Specifications Guideline
  - Annex I.12- Tritium Safe Handling Guideline
- **II. PBS and Interface Management System**
- **III. 3D MockUp**
- **IV. Compilation of Safety-related reports**
  - Annex IV.1-Safety Important Class (SIC)
  - Annex IV.2- Confinement Strategy
  - Annex IV.3- Tritium Source Term
  - Annex IV.4- AF Safety Report
  - Annex IV.5- LF Safety Report
  - Annex IV.6- CF Safety Report
  - Annex IV.7- TF FMECA
  - Annex IV.8- TF Safety Requirements
  - Annex IV.9- PIES
- **V. RAMI**
- **VI. Licensing Scenarios**
- **VII. IFMIF Beam Dynamics**

SYSTEM DESIGN DESCRIPTION DOCUMENTS (DDDs)

- **Test Facility(TF)**
  - Test Cell, Access Cell and Test Module Handling Cell
  - TF Auxiliaries
  - TF Remote Handling
  - Test Modules
    - High Flux Test Module (HFTM) - Vertical
    - High Flux Test Module (HFTM) - Horizontal
    - Start-Up and Monitoring Module (STUMM)
    - Creep Fatigue Test Module (CFTM)
    - Tritium Release Test Module (TRTM)
    - Liquid Breeder Validation Module (LBVM)
    - Low Flux Validation Module (LFVM)
- **Lithium Facility (LF)**
  - Lithium Facility (Integral Target Assembly)
  - Target System - Bayonet Concept
- **Accelerator Facility (AF)**
  - Injector
  - Radio Frequency Quadrupole (RFQ)
  - Medium Energy Beam Transfer (MEBT)
  - Superconducting RF Linacs
  - High Energy Beam Transfer (HEBT)
  - Radio Frequency (RF) Power
  - Diagnostics
  - Beam Dumps
  - Accelerator Auxiliaries
- **Conventional Facility (CF)**
  - Building and Site Infrastructure
  - Electrical Power System
  - Heat Rejection System
  - Heating, Ventilation and Air Conditioning System (HVAC)
  - Service Gas System
  - Service Water System
  - Solid Waste Treatment System
  - Liquid Waste Treatment System
  - Exhaust Gas Processing System
  - Fire Protection System
  - Radiation Monitoring System
  - Central Control & Common Instrumentation
  - Access Control & Security System

Figure 3. List of documents produced in the EDA phase

2.2 *EVA, the Engineering Validation Activities*

The engineering validation activities focused on the three most technologically challenging equipment, namely, the accelerator, the lithium loop and the test modules addressing all possible aspects to allow a rapid construction, with no technological challenges remaining open whenever the decision for its construction arrived, and allowing the continuous and stable operation of each IFMIF subsystem. The activities were substantially wider that what is here highlighted, details of the full scope are provided elsewhere [7]. All the Target Facility validation activities (with the exception of on-going corrosion/erosion tests in Lifus 6 lithium loop in operation by ENEA in Brasimone) have been accomplished [8,9,10]. All the Test facility validation activities have been accomplished [9,11] with full success in most of the assigned mandates. Only the prototype accelerator under installation and commissioning in Rokkasho remains to be validated. The validation of the most technological challenges, perceived in past phases as potential showstoppers is being achieved through the following hardware:

- the Linear IFMIF Prototype Accelerator (LIPAc) under installation in Rokkasho (CEA, CIEMAT, INFN, SCK-CEN, QST) [12,13]]
- the EVEDA Lithium Test Loop (ELTL) in Oarai [8,10], complemented by corrosion experiments performed at the Lifus 6 lithium loop at Brasimone (ENEA)
- the High Flux Test Module tested in the helium loop HELOKA [11] in Karlsruhe (KIT)
- Bayonet backplate remote handling in Brasimone (ENEA) [14]
- Small specimens (QST) and their fitting and removal in irradiation capsules in hot cells (KIT) [15]

In addition, the potential corrosion and erosion phenomena induced by the presence of N solved in the flowing lithium has also been studied with developments towards purification of N in the ELTL and experiments to determine the degradation of RAFM specimens exposed to flowing lithium at IFMIF relevant conditions in Lifus6 in Brasimone (ENEA) [16].

In the future paper to be published in Nuclear Fusion details of the aforementioned points will be explained.

3. Conclusions

The success of the EDA phase of IFMIF, delivered on schedule within the 6 years allocated, with a design backed by the parallel successful validation activities of the main technological challenges within the on-going EVA, is allowing to soon undertaking in a reliable manner the construction on schedule and cost of a Li(d,xn) fusion relevant neutron source [17].

In the EDA phase [6] significant advancements have been introduced into the design of the 5 major systems, resolving technical issues remaining from previous design phases [18]. The main ones are: the irradiation modules have no more a shielding function, by this change, the irradiation has been significantly gained in flexibility as alike to greater ease in modules positioning; the remote handling equipment has been improved allowing an increase of the reliability and a decrease of the cost; the Drift Tube Linac in the Accelerator Facility has been replaced by a Superconducting Radio-Frequency Linac, with a significant reduction in beam losses and operation costs; as a consequence, the RF system could be better modularised; the Quench Tank of the Li loop, previously included inside the Test Cell, has been re-located outside, with a reduction of the tritium production and, in addition, the operations required to exchange the Quench Tank, in case of failure, have been simplified; the Li loop has now two intermediate secondary cooling oil circuits, reducing the risks associated with the presence of Li, reducing the thermal gradients in the heat removal system and avoiding potential water boiling in case of loss of water flow; the liner and biological shielding of the Test Cell can now be cooled with water, enhancing the efficiency and economy of the related sub-systems, by adding a liner in the Li Loop Room; the Li Loop has now a by-pass, allowing more flexibility during its operation; most of the safety critical operations linked to the manipulation of the irradiated modules and Target Assembly have been concentrated in a relatively small Hot Cell; Injector design has been improved by adding a supplementary extraction electrode gaining in availability and a chopper that will ease the commissioning of the accelerators, and the maintenance strategy has been modified to allow a shorter yearly stop of the irradiation operations and a more careful management of the irradiated samples.

The on-going success of the EVA phase is overcoming all historical technical showstoppers [17] with the 125 mA CW at 40 MeV accelerator remaining as the only remaining technical challenge to validate, which will be realized with the operation of the 125 mA CW at 9 MeV deuteron beam of the Linear IFMIF Prototype Accelerator, presently under installation and commissioning phases in Rokkasho [12,13].

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