The IFMIF/EVEDA Project: Outcome of the first Engineering Studies

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on behalf of the Project Team and the numerous Institutes involved

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Abstract: On 5 February 2007 was signed in Tokyo the Broader Approach Agreement between Euratom and the Government of Japan. Among the three projects of this agreement, the Engineering Validation and the Engineering Design Activities (EVEDA) of IFMIF aim, within 6 years, "to produce a detailed, complete, and fully integrated engineering design of the International Fusion Materials Irradiation Facility (hereinafter "IFMIF") and all 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, the engineering design of IFMIF to enable its rapid construction".
IFMIF is an accelerator driven neutron source consisting of two deuteron accelerators bringing two intense beams carrying each of them 125 mA to an energy of 40 MeV. These beams interact with a 25 mm-thick liquid lithium flow circulating at a speed of nominally 15 m/s and generate an intense flux of neutrons whose energy is centered at 14 MeV, the energy of D-T fusion reactions. Three main systems constitute this facility:

- The Accelerator
- The Lithium Target
- The Test Facilities

Because of the characteristics of these systems, far beyond the state of the art, prototypes will be designed, built and tested during EVEDA to support the engineering work of IFMIF.
The project was officially launched in June 2007. The main first activities were mainly centered on the preparatory work for the prototypes, with detailed thermal, thermo-mechanical, neutronics, etc. calculations and the first engineering work. Most of this work is common to the IFMIF design. Preliminary technological demonstrations have also been performed (RFQ brazing, backplate welding, erosion and corrosion measurements, etc.).

1. Introduction

Considering the urgent need to develop more environmental friendly sources of energy, fusion is clearly a major option gathering many advantages. ITER should make the scientific demonstration of its feasibility but many nuclear aspects will not be tackled by the machine, such as:

- Neutron budget about one percent of the fusion power plant;
- Fuel cycle partially demonstrated;
- Availability and reliability not considered as major objectives.

The full nuclear environment will be probably one of the most challenging aspects of the machine(s) to be built after ITER: divertor technology enabling the removal of the heat while compatible with the neutrons irradiation, self consistency in tritium production, structural materials withstanding the neutron damages, etc. Today, only partial information is available on material behavior in fusion power plant relevant conditions. This crucial information must become available in order to dimension and license the fusion demonstrator(s), DEMO(s). The international community considers that a dedicated facility is necessary to characterize these materials before the detailed engineering work on DEMO. After having considered many concepts, the choice of an accelerator driven neutron source has been made. This concept has the advantage of using rather robust and proven technologies, producing a neutron spectrum well in accordance with what is foreseen for a fusion power plant and producing a ratio dpa / He generation also similar to the one expected in the structural materials of DEMO. The installation should be able to operate in continuous with a rather high availability and produce an amount of neutrons similar to the one of DEMO (typically 10^{18} neutrons/m^2/s in the highest irradiation zone).

The principle of the International Fusion Materials Irradiation Facility (IFMIF) is the following:

- Two linear accelerators, carrying each of them an intensity of 125 mA of deuterons bring their energy to 40 MeV.
- These two beams, operating in continuous wave (CW) shaped in the High Energy Beam Transport (HEBT) line to have a cross section of 200 × 50 mm^2 interact with a curtain of liquid lithium of 25 mm thick flowing at a nominal speed of 15 m/s in front of them.
- The interaction generates a large amount of neutrons with an energy peak of 14 MeV, as the D-T neutrons of fusion reactions, which interact with materials samples located in three main areas filled with test modules.
- Post Irradiation Experiment hot cells complete the facility.

The following figure synthesizes its principle.

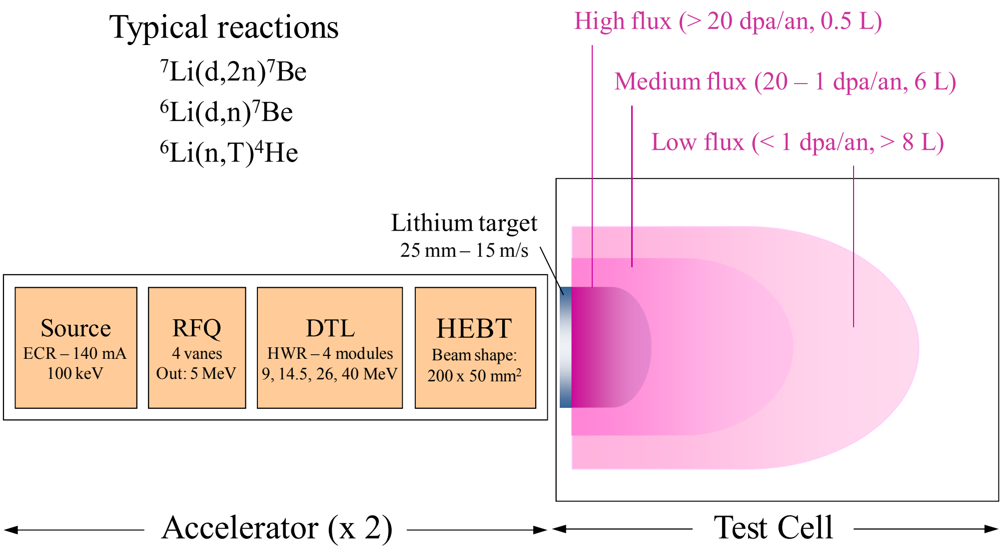

Figure 1: IFMIF is constituted of 3 main systems:
the Accelerator Facility, the Lithium Target Facility and Test Facilities

After several conceptual phases, the Engineering Validation and Engineering Design Activities (EVEDA) of IFMIF have started in the frame of the Broader Approach agreement signed between Europe and Japan on 5 February 2007 and which harmoniously completes the ITER program launched 2 months and a half before. Two kinds of activities structure the project:

- The main goal is to deliver by June 2013 the detailed engineering design file of IFMIF, enabling its rapid construction, similarly to the EDA phase of ITER;

- The validation of the main systems of the facility thanks to the design, manufacturing and tests of three main prototypes (similarly to the 7 large ITER EDA projects):
  - The low energy part of the accelerator (up to 9 MeV), tested at full current (125 mA) in CW at Rokkasho, Japan;
  - The lithium target, with a width of lithium flow at a reduced scale of 1/3, but including all purification (hot and cold traps) and monitoring systems foreseen for IFMIF, and tested at Oarai, Japan;
  - The High Flux Test Module's main components, with in particular the irradiation of scale 1:1 rigs and thermo hydraulic demonstration of the modules.

Many Institutes in Europe and in Japan contribute to this project, under the overall coordination of a Project Team, located in Rokkasho, Japan. One year after its official start in June 2007, several concepts proposed in the Comprehensive Design Report (CDR) [1] have been confirmed or strongly modified. This paper proposes to summarize the work performed up to now and to show a rapid picture of the present situation.

2. Accelerator Facility

The accelerator facility [2] can be roughly divided in 6 main subsystems:

- The **Injector and its associated Low Energy Beam Transport (LEBT) line**; the electron cyclotron resonance source, associated with a set of 4 shaping and accelerating electrodes generate the initial beam of 140 mA, 100 keV.
- The **RadioFrequency Quadrupole (RFQ)**: a four vane structure, with a total length of 9.78 m and divided in 8 main modules and 2 special ones at each end will bunch and then accelerate the beam to an energy of 5 MeV. A special care has been taken to minimize the beam losses, and privilege the low energy part for the unavoidable ones in order to minimize the activation; a great care also is made in the temperature monitoring of this delicate device.
- The **Matching Section**: this section, equipped with some diagnostics optimizes the beam before its acceleration in the DTL.
- The **Drift Tube Linac (DTL)**: the choice of a superconducting DTL using half-wave resonators has been made in May 2008, considering the numerous advantages of this technology: large existing operating base, minimized losses, which is of course of particular importance for an accelerator working in CW, shorter length (and real estate economies), easier integration of focusing magnets close to the accelerating cavities, etc. A sketch of the first module (tested during the EVEDA phase) is given in Figure 2.
- The **High Energy Beam Transport (HEBT) line**: this line propagates the beam to the liquid lithium target and transforms the initial cylindrical beam into a rectangular cross section of 200×50 mm^2. During EVEDA, a special diagnostic plate will be inserted in the HEBT to perform a thorough characterization of the beam, before its collection in the beam dump.
- The **RF system** has been standardized, to decrease its cost: two power units are considered: 105 and 220 kW. Each is composed of a pre-driver, a first amplification stage by means of tetrodes (output power of 11 kW, depending on the system) and the final amplification stage, also based on tetrodes. A total of 40 units of 105 kW and 64 units of 220 kW are required for the two linacs of IFMIF.

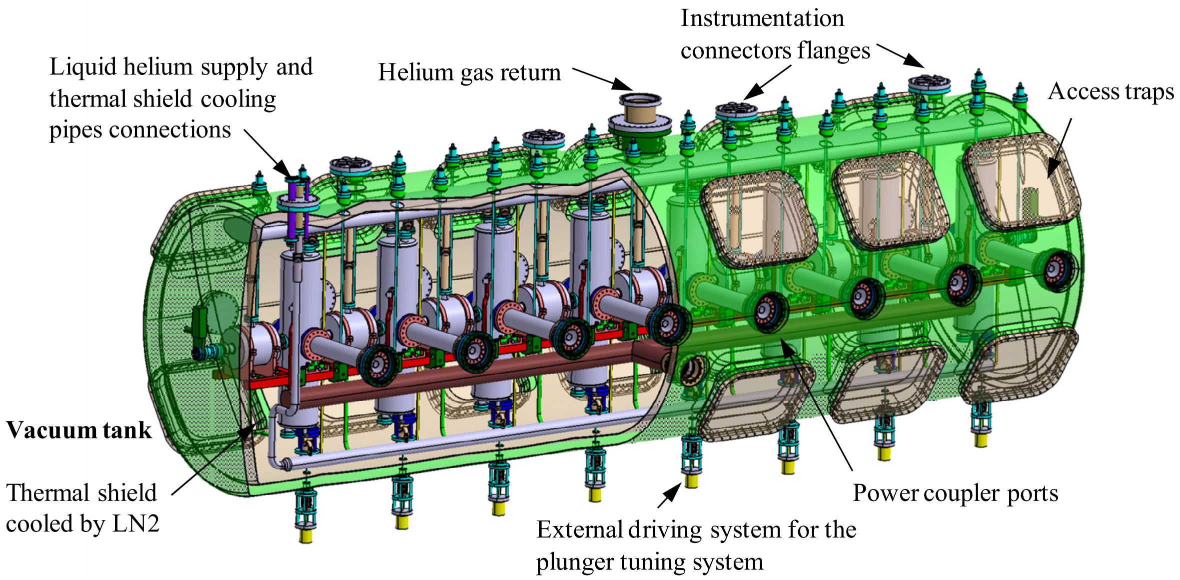

Figure 2: General view of the first cryomodule of the DTL, to be tested during EVEDA

A Beam Dump [3], a classical three-layer control system, with a breakdown between the supervision system, and sub-system devoted electronics and facilities, including the construction of a dedicated building at Rokkasho, complete the work required for the prototype.

3. Lithium Target Facility

The second main system of IFMIF is the liquid lithium target, whose principle is summarized in Figure 3 (see also [4]). The main specifications, common to EVEDA and IFMIF target assemblies in normal operation, are as follows:

- Li speed at nozzle exit: 10-20 m/s (operation range)
- Li flow thickness and stability: 25 ±1 mm
- Li temperature: 250-300 °C (control range: 200-350 °C)
- Materials: RAF steel (F82H, Eurofer): backplate, possibly nozzle
  Stainless steel 304L, 316L: other parts
- Vacuum pressure: 10^{-3} Pa (at free-surface during operation)
  10^{-4} Pa (before Li charge)

The main difference between the IFMIF and EVEDA loops is the width of the lithium flow on the backplate: 260 mm for IFMIF and 100 mm for the test loop, which will built and tested at Oarai, Japan, in a department of JAEA already equipped with sodium and NaK facilities.

Two options for the backplate are considered today, with the objective to propose a preferred one at the end of EVEDA:

- A “bayonet” concept [5], [6], based on a sliding backplate tightened with an o ring
- A welded lip sealed backplate [7]

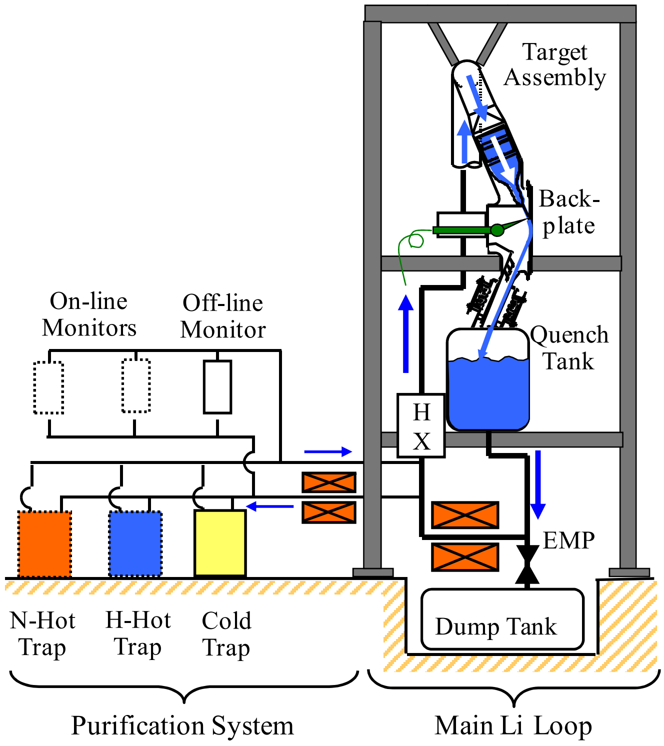

Figure 3: Sketch of the lithium loop, with its main subsystems: the main Li loop with the target assembly, the quench tank, the electromagnetic pump and the purification and monitoring sub-loop

Thermo-mechanical calculations for the lip-seal proposal led to the insertion of a stress mitigation ring close to the lip, which strongly relaxes the stresses in the plate. Tests for asymmetric welding between 316L and F82H by TIG were performed not evidencing particular issues, while hardness of YAG-welded 316L/316L decreased somewhat in the fusion metal [8].

As for the Bayonet technology design of the test rigs to test the sealing capability of the Helicoflex HNV 200 type gasket against Li infiltration and corrosion induced damage has been completed. Design of the rigs to test dicronite treatment in place of lubricants by using ion beam irradiation has been completed. To evaluate the impact of the swelling phenomena on the functionality of the tightening system of the backplate, a preliminary evaluation of the damage rate on the bolting area of the backplate has been performed.

Preliminary neutron damage mapping of the backplate was calculated to provide input data for bayonet concept evaluation and qualification. Thermo-mechanical analysis of the backplate and its connecting part of the target assembly under nuclear heating in normal operation of IFMIF was done. Thermo-mechanical computations with setting up of a 3D FE model for the backplate was started and material properties before and after irradiation were acquired.

With respect to hydro-dynamics characteristics of the lithium flow, a nearly constant curvature radius of the backplate, from the nozzle exit to the quench tank is now proposed to avoid the generation of instabilities, in particular upstream. Recent experiments indeed show the importance of such optimizations, as well as the nozzle shape.

An erosion/corrosion loop, Lifus 3, was completely commissioned, apart for the purification system, and filled with lithium. A purification system, consisting of three traps, was manufactured and should be installed on the Lifus 3 loop in 2008. The flow meter, filter and monitoring system were provided. First erosion/corrosion test of 1,000 hours with AISI 316 and Eurofer 97 specimens were concluded showing a better behavior of martensitic steels [9], but these experiments will continue to confirm this first tendency, in particular once the purification system is installed in Lifus 3. Experiments on reaction between Li and atmosphere gases were conducted at various temperatures. The removal and cleaning method and experiments on Li combustion were evaluated.

An intense preparatory work on the purification and monitoring systems was conducted during this first project phase:

- The removal of nitrogen in Li down to 10 wppm seems to be achievable by hot trap with titanium. To avoid the formation of TiN surface layer that suppresses further nitrogen gettering, Nitrogen gettering with Fe-Ti alloy or V-Ti alloy has been performed. These experiments, made in static conditions, conducted to the need to simulate in more realistic dynamic conditions the IFMIF purification system. Conceptual design of such a system has been made.
- The removal of tritium dissolved in Li down to 1 ppm requires the operation of hydrogen absorption by metallic Y at 250°C; however the removal of tritium down to 1 ppm by a hot trap has never been proved experimentally because of an oxide layer formed on as-received Y surfaces [10]. Basic performance of the small Y plate pre-treated by acid HF for removing oxide was clarified and conceptual design of a tritium hot trap for flowing Li loop has been done.

4. Test Facilities

In the Test Cell (see Figure 4), an optimization of the different modules is still undergoing, based on more complete neutronics calculations [11]. The challenges of the Test Facilities design are described in [12]. Three categories of modules are foreseen:

- The **High Flux Test Module** (HFTM): all specimens of reduced size are immersed in a NaK bath contained in rigs; these rigs are themselves heated thanks to an external heater located in grooves and the whole set of 12 rigs is regulated in temperature via a helium flow.
- **Medium Flux Test Modules**: 3 modules are contemplated:
  - A Creep Fatigue Test Module
  - A Tritium Release Test Module
  - A Liquid Breeder Validation Module
- A **Low Flux Test Module**: a region where functional materials could be tested.

With the exception of the HFTM where substantial progress was performed, thanks to previous and advanced conceptual design of this module, including the fast procurement procedure for the HELOKA-LP loop at FZK, most of the activities during this first period were focused, as foreseen, on the definition of the main activities to be performed along the EVEDA phase, the review of documentation and the definition of boundary conditions [13]. There was also much progress on neutronics calculation as a previous step to some conceptual designs. Review and calculations for the Fission Microchamber also helped to define the conceptual design and the best options for the radiation monitor. Some calculations were also performed for the Creep Fatigue module and the Tritium Release Module related with the control of temperature of specimens according to previous Conceptual Designs.

Main activities in the Test Facilities may be summarized as follows:

- The progress regarding the HFTM was focused on the design optimization, through experiments in the helium loop ITHEX, thermohydraulic calculations, the design of the Na/NaK filling station and the test of the brazing technique. An individual cooling of each row of rigs is now foreseen, enabling a much better control of the temperature of the samples (see Figure 3).

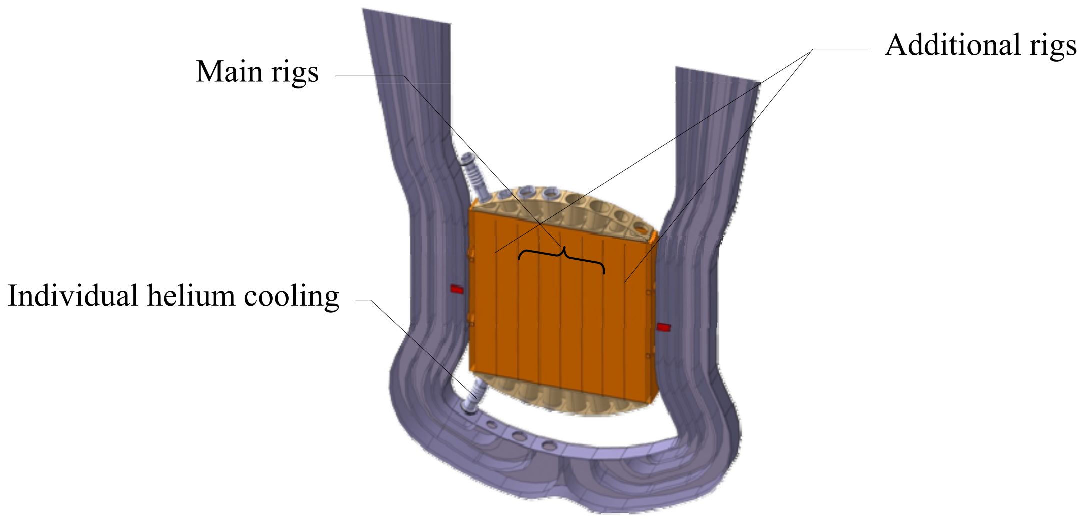

Figure 4: New set-up of the High Flux Test Module, with an individual cooling of each rig and the addition of lateral rigs

- Design and procurement of the dedicated helium low pressure loop at Karlsruhe, HELOKA-LP, have been made, with the objective to complete the assembly early 2009.
- A first detailed conceptual model of the creep fatigue test module is now available, showing that the control of the temperature of samples can be obtained by an appropriate helium mass flow.
- Thermohydraulic analysis of two alternative conceptual designs for the tritium release test module was performed in view point of the temperature control of the test specimens.
- Burn up calculation of fission microchamber was performed to analyze the good performance of the radiation monitor following long irradiation periods.
- The IFMIF Target and Test Cell (TTC) is under complete review, (i) to mechanically separate the shielding from the delicate modules (ii) to improve the versatility of the Test Cell (iii) to ease the Remote Handling of the modules and of the target.
- A first review of measurement equipments and requirements in PIE Cells was performed.
- Development of tools for the implementation of new procedures that will be defined along the project was performed. An initial review of RH operations, assessment of the time required for the maintenance period, review of RH requirements of test cell components, assessment of feasibility of commercial RH equipment and tools and identification of open issues were performed.

- The nuclear response was calculated for the HFTM to identify the optimum position for tungsten specimens and for the Creep Fatigue Module to obtain a map of radiation damage and heat load in the frame of the module.

5. Conclusion

After one year of work, the main concepts resulting of the previous phases of IFMIF have been confirmed. Nevertheless, several important modifications were brought, which aim at securing the design and use more modern technologies. The accelerator for example has been deeply modified and optimized. Purification techniques, mandatory to minimize the erosion and corrosion of the lithium are being developed. Some uncertainty subsists on the lifetime evaluation of the backplate and both concepts continue to be developed. Several Test Cell arrangements are also being developed in order to improve the flexibility of the Test Modules, and offer to IFMIF's customers more versatility. In conclusion, no showstopper has been identified and the future work will concentrate on the prototype detailed design and start of manufacturing, keeping the objective of IFMIF engineering report deadline of June 2013.

Acknowledgement

IFMIF/EVEDA is one of the three projects of the Broader Approach agreement between Euratom and Japan.

References

[1] IFMIF Comprehensive Design Report, by the IFMIF International Team, an activity of the International Energy Agency, Implementing Agreement for a Program of Research and Development on Fusion Materials, January 2004
[2] Alban Mosnier: Status of the IFMIF/EVEDA accelerator, 25th SOFT, September 2008
[3] Beatriz Brañas: Design of a beam dump for the IFMIF-EVEDA accelerator, 25th SOFT, September 2008
[4] Hiroo Nakamura: Status of engineering design of liquid lithium target in IFMIF-EVEDA, 25th SOFT, September 2008
[5] Gioacchino Micciché: IFMIF target assembly: Enhancement of the remote handling strategy for the replaceable backplate bayonet concept, 25th SOFT, September 2008
[6] Pietro Agostini: Approach to the lifetime assessment of the bayonet back plate for IFMIF target, 25th SOFT, September 2008
[7] Makoto Miyashita: Development of remote handling technology of liquid lithium target and replaceable lip seal backplate in IFMIF-EVEDA, 25th SOFT, September 2008
[8] Kazuyuki Furuya: Effect of different welding rods on mechanical property of dissimilar weld zone in F82H backplate for IFMIF lithium target, 25th SOFT, September 2008
[9] Alessandro Gessi: Explorative experiment of steel erosion/corrosion in high speed flowing lithium, 25th SOFT, September 2008
[10] Satoshi Fukada: Tritium removal by Y hot trap for Li purification of IFMIF target, 25th SOFT, September 2008
[11] Stanislav Simakov: Impact of D-Li source photons on the nuclear responses in the IFMIF test modules, 25th SOFT, September 2008
[12] Joaquin Molla: IFMIF test facilities: Main challenges for final engineering design phase, 25th SOFT, September 2008
[13] Frederik Arbeiter: Prospective testing and design validation program for the IFMIF high-flux test module within the EVEDA phase, 25th SOFT, September 2008