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Start of the engineering validation and design phase of IFMIF

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ABSTRACT

In the framework of the Broader Approach agreement, the main objective of the Engineering Validation and Engineering Design Activities (EVEDA) of IFMIF is 'to produce a detailed, complete and fully integrated engineering design of the International Fusion Materials Irradiation Facility 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 duration of the project is 6 years, starting from June 2007. The main technological and scientific challenges of IFMIF are recalled in a first part, leading to a proposal of validation activities, described in the second half of this paper.

1. Introduction

All along the (long!) history of conceptual activities of an irradiation facility for fusion materials characterisation, many concepts have been proposed. The last phases of these conceptual studies, performed under the auspices of the International Energy Agency, concluded that the best performance/cost compromise was based on an accelerator driven source.

Schematically, its principle is the following: two parallel deuteron accelerators bring their beams, carrying each of them 125 mA, to an energy of 40 MeV. These two beams interact with a 25 mm thick liquid lithium 'curtain' flowing at about 15 m/s in front of them. The high flux of neutrons generated, whose energy spectrum is rather representative of the one calculated for a fusion demonstration reactor, irradiate the test cell modules, located just behind the lithium target, and where samples of materials are placed. Post Irradiation Experiment cells where the irradiated samples will be characterised complete the facility.

This facility is described in the Comprehensive Design Report [1], summarising the conceptual studies performed earlier in another context. Fig. 1 below, extracted from this report, shows the main systems of the facility.

The Engineering Validation and Engineering Design Activities cover mainly two aspects:

- the validation though the design, manufacturing, commissioning and test of the most challenging systems of IFMIF:
  - The low energy part (up to about 10 MeV) of one of the two accelerators,
  - The lithium loop and target (at a scale 1/3) with all its purification systems,
  - The elements of the High Flux Test Module at a scale 1:1, associated to an irradiation programme;
- the Engineering Design Activities of IFMIF, with the delivery of a Final Design Report, detailed cost evaluation and technical specifications for the urgent systems to build, enabling the Party(ies) to start the construction of IFMIF, if it (they) so wish, in a framework still to define.

2. Scientific and technological challenges of IFMIF

Even if the technologies chosen during the conceptual phase are 'moderately aggressive' (*sic*), several important features will have to be demonstrated for the safe construction of IFMIF. The most important ones are recalled hereafter.

The Test Facilities, shown in Fig. 2, core of the installation, require a special attention, in particular on the following points:

- Control of irradiation conditions requires a system of temperature regulation. In the High Flux Test Module, the reference design is based on helium cooling of the rigs where the samples are encapsulated, associated with a heater on the capsule itself. Hydrodynamic performance and resistance of the heater to the irradiation must be tested.
- Instrumentation for dose measurements, which will also be subject to intense irradiation inside IFMIF, must also be tested under relevant irradiation conditions.
- The other modules (the three ones of the medium flux zone in particular) use technologies in a highly radioactive environment. For example one of the three Medium Flux Test Modules contains *in situ* creep fatigue samples: the life time of the actuators must be carefully evaluated.

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[1] On behalf of the IFMIF EVEDA project team and contributing Institutes.

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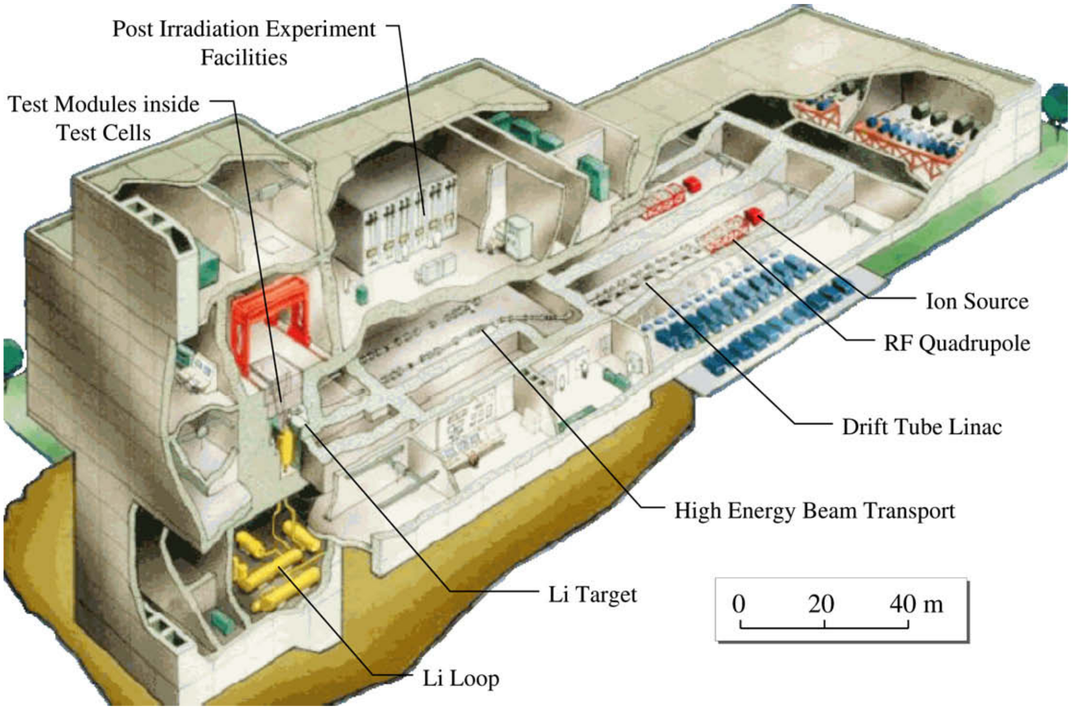

Fig. 1. Overall view of the IFMIF installation, showing the main parts of the plant: the two accelerators, the liquid lithium target and its purification loop, the test facilities behind the lithium target and the post irradiation facilities and the surrounding building.

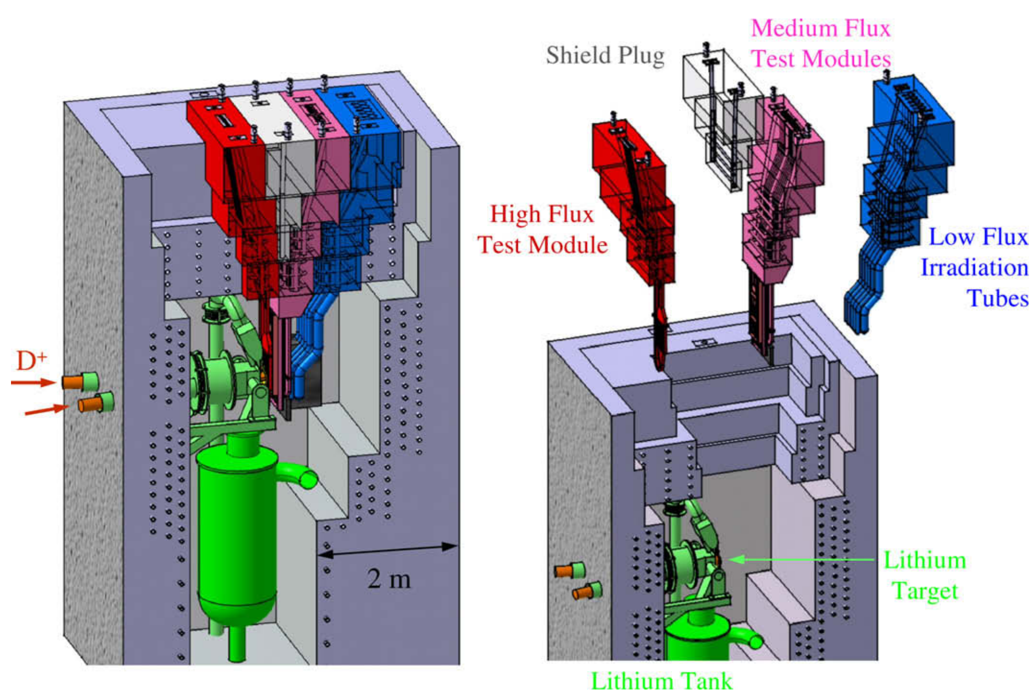

Fig. 2. Schematic view of the lithium target facilities and the test facilities. In the high flux test module (20–50 dpa) about 1000 samples, positioned in temperature controlled boxes, will be irradiated. The medium flux test module (between 1 and 20 dpa) can contain for example several tests as creep fatigue tests under irradiation, *in situ* tritium release experiments. The low flux irradiation Tubes are not yet defined and could be used to test ceramic insulators, RF windows, or even superconducting materials.

- Irradiation conditions and removal of the heat generated by the neutrons irradiation, the tight mechanical interface between the different systems in the Test Cell, as well as the overall Remote Handling tools are other issues of the Test Facilities.

The lithium target (see its schematic in Fig. 3) represents also a challenging project, in a rather virgin domain:

- The optimisation of the neutron flux and safe operation of the lithium flow and backplate requires a very fast flow of lithium with severe constraints on its thickness (±1 mm over 25 mm). Hydraulics, thermo-hydraulics and even magneto-hydrodynamics (MHD) must be studied to guaranty a safe behaviour.

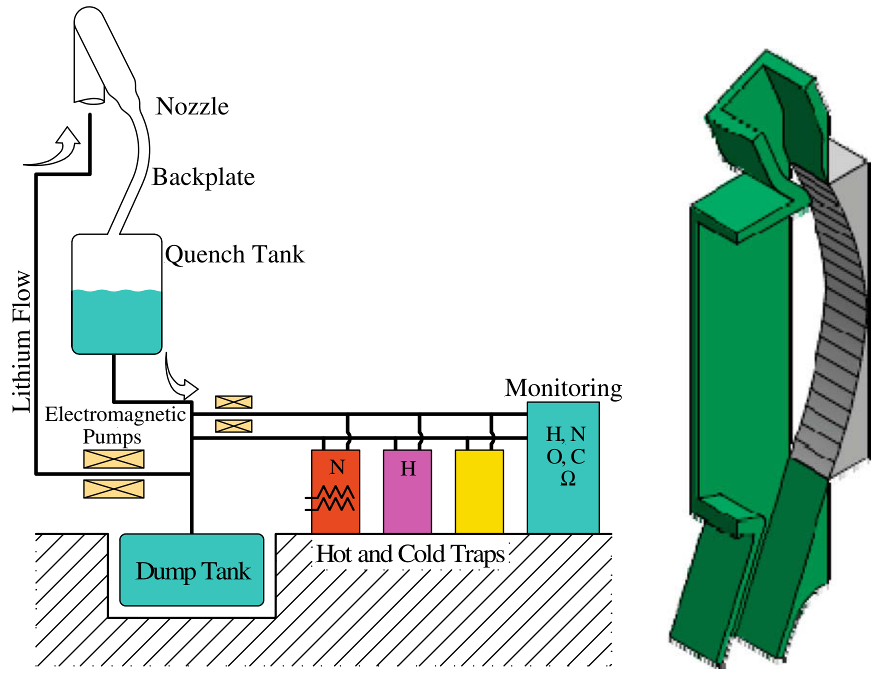

Fig. 3. Principle of the lithium loop and of the target: the nozzle above the backplate injects the liquid lithium at about 15 m/s, its temperature being 250 °C. The lithium is recovered in the quench tank. The loop contains hot and cold traps to maintain the purity of the lithium below a few wppm. The sketch on the right represents a typical shape of the backplate, the aim being to minimise the risk of turbulent flow.

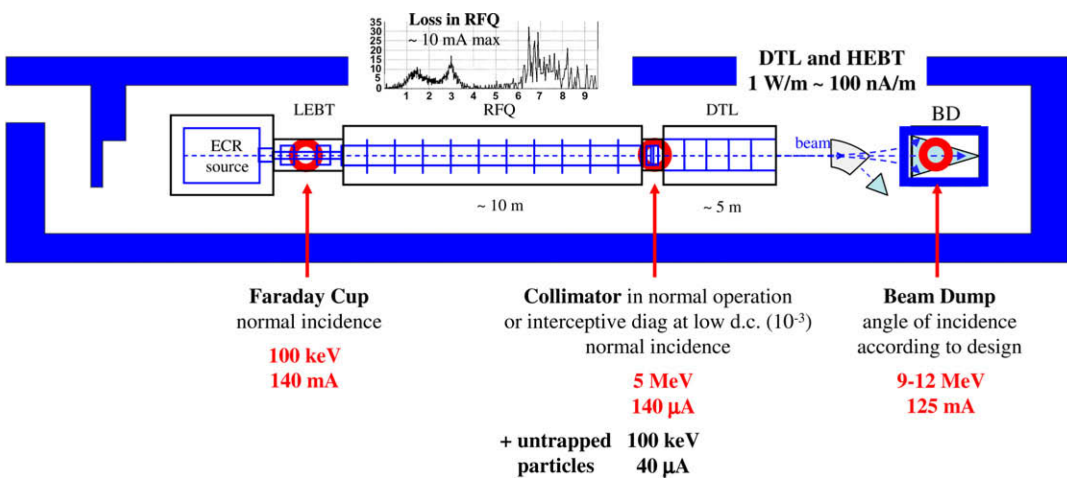

Fig. 4. Example of calculation of beam loss along the accelerator. In order to enable hands-on operation, their minimisation is mandatory. The figure shows the main concentration of losses: the Faraday cup, in the LEBT, in the matching section and mainly in the beam dump. Present calculations show very low losses in the RFQ and no loss in the DTL.

- The purity of lithium, which will be used at about 250 °C, must be particularly high to avoid erosion (in particular of the nozzle that will propel it on the backplate). Nitrogen, hydrogen and oxygen in particular will have to remain below the level of typically a few 10 wppm.
- Corrosion must also be minimised (same requirements as for the purity), in order in particular to minimise the resulting erosion and handle the smallest amount of activated corrosion products.
- Because of its irradiation (about 50 dpa per year) and degradation of its mechanical properties, the backplate will have to be regularly replaced (probably once per year). Technologies to enable a fast replacement under controlled atmosphere must be studied.

Last key system, the accelerator will be the first one ever built carrying such an intense beam current. Special care must thus be drawn on:

- All thermal loads (operation in CW at 175 MHz), in all structures.
- Beam space charge and instabilities.
- Beam interception, in order to minimise the thermal load and activation of the structures by the deuterons, and impinging its hands-on maintenance (see Fig. 4).
- Reliable operation, the availability of IFMIF being a major challenge,

- And of course all ‘conventional’ issues (mechanical accuracy, interface, comprehensive set of diagnostics, etc.) encountered in such linear accelerators.

Nota bene: one important feature will not been tackled in the current scope of EVEDA: the actual interaction between the deuteron beam and the liquid lithium flow. The beam will indeed carry an energy density of 1 GW/m^2 that will be deposited inside the lithium flow; this could generate instabilities because of the resulting temperature profile in the thickness of the lithium.

3. Organisation of the project

The structure of the Broader Approach agreement is rather simple. The Broader Approach Steering Committee is the international structure which has the decisional power.[2] Each project is advised by a scientific committee, called Project Committee.

This agreement is based mainly on ‘in-kind’ contributions from both Parties. Its legal implementation is thus ensured by the Domestic Agencies created in the framework of the ITER treaty: the joint undertaking ‘Fusion for Energy’ in Europe, the JAEA in Japan. Nevertheless, contrarily to the ITER treaty, as only a limited number of countries contribute to the Broader Approach in Europe, national Institutes as CEA, CIEMAT, INFN, FZK, CRPP or ENEA play a major technical and contractual role. In Japan, JAEA is the major scientific contributor; many Universities or Institutes are also involved in the validation tasks, and even the engineering tasks, such as Hachinohe, Kyoto, Kyushu, Nagoya, Osaka, Tohoku and Tokyo Universities or Institutes.

The project is managed by a ‘Project Team’, located in Rokkasho. The coordination of all activities between the Parties is ensured by dedicated groups inside this team, each of them in charge of one of the three main systems of the plant: the Accelerator, the Target and the Test Facilities. The Project Team is also in charge of the design integration and will deliver *in fine* the design engineering file for the construction of IFMIF, as well as its cost, site specification and generic site safety report.

A great care is taken to balance scientific knowledge and benefit of existing knowhow in both Parties.

- The accelerator for instance, designed mainly in Europe, will be tested in Rokkasho, in a specific building provided by Japan.
- The lithium loop will also be mainly designed and tested in Japan, at Oarai, where an important infrastructure and knowledge already exists, developed in the framework of fast breeder research. The main European contributor is ENEA (centre of Brasimone, where an important competence on remote handling and lithium loop exists).
- On the other hand, Test Facilities activities will lead mostly to experimental work in Europe, such as irradiation programme, helium cooling performance, Japan being in charge of the design of an alternative set-up of the samples in the High Flux Test Module and some tasks on the extrapolation confidence from small samples (‘Small Specimen Test Techniques’).

4. Validation activities of the project

Since its official launching in June 2007, the project has been structured, and a Project Plan has been established. The following sections will describe mainly the validation activities, the engineering phase of IFMIF, starting later will be described in a future paper.

In general, the first activities deal with the design of the prototypes, in particular for the Accelerator and the Target Facilities, the Test Facilities being more advanced and their detailed design being able to start sooner.

4.1. Test Facilities activities

The validation activities of the Test Facilities are mainly focused on the High Flux Test Module (HFTM) and the fabrication, then irradiation of full-size HFTM for the vertical set-up. This task involves the use of heavy experimental structures: nuclear irradiation reactor(s), helium loop, etc. The purposes of such tests are in particular:

- Check of the irradiation thermal conditions, these ones being ensured by a combination of helium flow, and heating of the samples by means of a heater located in a groove around the capsule. Tests in the helium loop will check the thermo-mechanical and hydraulic behaviour.
- The technological demonstration (welding, brazing, assembly, etc.) by the construction of a full set-up.
- Irradiation programme should check, at a less stringent flux than IFMIF, the behaviour of the scale 1:1 capsule: electrical isolation, thermal quality of the NaK surrounding the samples, analysis of the behaviour of one of the most important instruments proposed to monitor the irradiation (gamma microchamber), etc. Heat due to nuclear heating, simulated in the prototype by electrical heater, will also have to be checked.
- Post irradiation analysis of all these elements (samples, capsule, heaters, microchamber, etc).

A full-size HFTM for the horizontal set-up will be designed, and a heater-integrated (H-I) plate and capsule will be fabricated and intensively tested.

With respect to the Medium Flux Test Modules, special attention will be devoted to the *in situ* creep test fatigue, and in particular the actuators providing the mechanical efforts to the samples.

4.2. Target Facility activities

Several experimental facilities will contribute to better understand lithium loop characteristics and provide a sound basis for IFMIF’s Target Facility construction.

The main one is the EVEDA test loop designed and built by JAEA at Oarai, with contribution from ENEA. This loop will be rather representative of IFMIF’s one, being constituted of all elements of the latter. The target itself will have a height at a scale 1:1, and only its width is reduced by a factor 3. Nevertheless all side effects should be affordable, only the central part being actually reduced. This loop will enable to tackle the following issues, recalled in the introduction above:

- Hydraulics and thermo-hydraulics of the lithium flow (laminarity, sensitivity to defaults, erosion of the nozzle, etc.);
- Purification system, by providing all hot and cold traps to maintain the lithium impurity level below the 10 wppm or so threshold;
- Possibility to exchange the backplate, both concepts (cut and weld and ‘bayonet’) being accessible in the EVEDA loop;
- Operation of specific diagnostics in a non-irradiated environment but other real conditions (vacuum and vapour pressure, temperature, and geometry).

[2] Let us recall that in addition to IFMIF/EVEDA two other projects, the satellite tokamak (major upgrade of JT-60) and IFERC (International Fusion Energy Research Centre in Rokkasho, with important computation tools and remote capacities), also belong to the Broader Approach agreement.

Two other lithium loops will help, in particular in the preparatory work during the first half of the project: the loop already in operation at Osaka University since a few years, which has already provided very important experimental results and the more recent Lifus 3 loop of ENEA, started during the summer 2007 at Brasimone, and enabling in particular parametric studies of erosion and corrosion with several materials.

Adimensional (i.e. based on constant Reynolds or Froude numbers for example, similarly to wind-tunnel tests for airplanes) studies will also be performed by using water loops (e.g. at Nagoya University).

The last set of experimental work is dedicated to the two options for the removal and exchange of the backplate:

- The *lip-seal solution*, based on the cutting and welding of lips by means of a YAG laser, but requiring the removal of the whole target assembly, will lead to technological tests, as early as 2008, its implementation in the EVEDA loop being planed at the start of its operation.
- The more ambitious 'bayonet' concept based on the lateral sliding of only the backplate, itself being bolted on the target assembly, for which all relevant technologies must be demonstrated: remote handling tool compatibility with the severe environment, swelling of bolts, sliding capacity with special lubricants, etc.

4.3. Accelerator Facility activities

The IFMIF accelerator, whose low energy section (up to about 10 MeV) will be tested at full current at Rokkasho, is classically composed of four subsystems:

- The *injector* (ECR driven source) and *Low Energy Beam Transport* (LEBT) line (140 mA – 100 keV): a similar source has been already successfully and reliably tested by CEA in CW with H^+ and pulsed regime with D^+ ions. Its optimisation (electrodes shape, emittance) does not pose *a priori* specific difficulties.
- The *RadioFrequency Quadrupole* (RFQ), bunching and acceleration up to an output energy of 5 MeV. The work is shared between INFN and JAEA, which provides the RF input couplers. A classical four vane structure is proposed, its main challenges being a very high accuracy (a few 10 μm) all along its about 10 m and minimisation of beam losses. Brazing technology, reasonable thermal load, cooling temperature accuracy and RF couplers require specific attention, tackled already in 2008.
- The *Drift Tube Linac* (DTL) and *Matching Section*: the reference solution is today a classical Alvarez room temperature DTL. Two alternative superconducting solutions are currently being studied in Europe: a CH structure, proposed by Frankfurt University, and a more conservative Half Wave Resonator (HWR) structure, proposed by CEA. Technical challenges (in particular beam interception) and their cost impact are being evaluated.
- The *High Energy Beam Transport* (HEBT) line and the *Beam Dump*: two lines must be studied for the EVEDA accelerator (10 MeV, circular cross section) and the IFMIF final line (40 MeV, and beam shaping to provide a rectangular beam footprint of $200 \times 50\ \text{mm}^2$). Few calculations are today available on the beam quality at the end, and thus must be strongly developed: energy spread, sharpness of the beam geometry, sensitivity to static and dynamic errors, etc. With respect to the beam Dump, its thermal load will of course require dedicated attention, as well as the minimisation of its activation.

Two other subsystems complete the Accelerator Facility main activities:

- The *RF sources and RF lines* (including circulators, etc.), split between CEA and CIEMAT,
- The *Rokkasho building and Utilities*, under JAEA responsibility.

5. Conclusion

Thanks to the implementation of the Broader Approach agreement (also opened to other ITER Parties) in parallel to ITER construction, the fusion community strongly improves the coherence of its overall programme, and shortens the time required to design and build the first power plant based on fusion energy. If a site is suitably chosen for the construction of IFMIF, the start of its operation could be almost simultaneous to ITER operation in tritium. A new essential phase of IFMIF is now starting with its engineering activities, which will last 6 years.

Acknowledgment

The Engineering Validation and Engineering Design Activities of IFMIF are one of the three projects of the Broader Approach agreement signed between Japan and the European Union on 5 February 2007 at Tokyo.

Reference

[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.