SUITABILITY AND FEASIBILITY OF THE INTERNATIONAL FUSION MATERIALS IRRADIATION FACILITY (IFMIF) FOR FUSION MATERIALS STUDIES

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Abstract

There is a global consensus among materials scientists and engineers that the qualification of materials in an appropriate test environment is inevitable for design, construction and safe operation of DEMOnstration fusion reactors as well as for calibration of data generated from fission reactor and accelerators irradiations. In an evaluation process based on a series of technical workshops it was concluded that an accelerator driven D-Li stripping source would be the best choice to fulfill the requirements within a realistic time frame. In response to this need, an international design team with members from Europe, Japan, USA and Russia has developed under the auspices of the IEA during a Conceptual Design Activity Phase (1994-96) a suitable and feasible concept for an accelerator driven D-Li stripping source. This IFMIF reference design is based on conservative linac technology and two parallel operating 125-mA, 40-MeV deuteron beams that are focused onto a common liquid lithium target with a beam footprint of 50 mm by 200 mm. The materials testing volume downstream the Li-target is subdivided into different flux regions: The high flux test region (0.5 liter, 20-55 dpa/full power year), the medium flux test region (6 liter, 1-20 dpa/fpy), and low flux test regions (>100 liter, < 1 dpa/fpy). The developed design was the basis fore the present Conceptual Design Evaluation Phase (1997-98) and for subsequent engineering oriented activities. Based on comprehensive neutron transport calculations, an evaluation of the irradiation parameters and the available test volumes has shown that the users requirements can be fulfilled. Major engineering efforts have been undertaken to establish an IFMIF design that is based on available and already proven technologies. The developed design includes extensive reliability, availability, maintainability as well as safety studies and is conceived for long-term operation with a total annual facility availability of at least 70%.

1. INTRODUCTION AND MISSION

The need to develop materials that can withstand the high-energy neutron flux environment expected for the first wall and blanket regions of deuterium-tritium (D-T) fusion reactors is recognized as one of the key challenges remaining in the program aimed at producing commercial fusion power. Structural alloys for first wall and blanket components, surface-protecting materials, and tritium- breeding ceramics belong to the category of materials, which are intensively exposed to high-energetic 14 MeV neutrons. At present an appropriate materials test facility which could adequately simulate this neutron environment is not available though it has been demanded at several occasions by the Fusion Materials Community and by high-ranking advisory boards like the Cottrell Blue Ribbon Panel and the Amelincks Senior Advisory Committee [1,2]. During the last ten years under the auspices of the International Energy Agency (Implementing Agreement for a Program of

Research and Development on Fusion Materials) a new step towards a suitable source was initiated to determine the test requirements, select suitable source concepts and assess their technical feasibility. In a series of workshops, starting with the San Diego Meeting in February 1989, the consensus was reached that the concept of an accelerator based source which utilizes the deuterium-lithium stripping reaction (D-Li-source) for neutron production was the only choice with the potential to fulfill the demanded requirements within a realistic time scale [3,4]. In a conjoint effort with the participation of the European Union, Japan and the United States and Russia as an associated member, an IEA-IFMIF-Conceptual Design Activity (CDA phase) was implemented end of 1994 for the International Fusion Materials Irradiation Facility (IFMIF). This design study was punctually finished end of 1996 and provided a reference conceptual design [5] as well as a detailed cost estimate [6]. The developed design was the basis for the current Conceptual Design Evaluation Phase CDE (1997-98). A subsequent engineering oriented phase with prototype development and testing of specific components should be started soon. Because the development of novel materials under the very harsh conditions of fusion environment needs a long lead time, an early decision for an IFMIF is urgent.

The mission of an intense neutron source like IFMIF is to produce high-energetic neutrons at sufficient intensity with an appropriate neutron spectrum in a reasonably large irradiation and testing volume. A facility of this type is primarily important and essential for an accelerated development and qualification of materials to be used in the first wall and breeding-blanket area. It should, however, also supply a test bed for other materials with a lower neutron exposure. With such a facility the most relevant part of an engineering database for irradiated materials should be generated up to the anticipated life-time. Since a large irradiation data base has been accumulated for many materials by experiments in fission reactors and accelerator-driven facilities, IFMIF could also provide calibration and validation of such data for fusion and identify possibly new phenomena which might occur due to the high-energy neutrons exposure.

2. BASIC IFMIF DESIGN

The basic design concept for this facility has been guided during the CDA-phase by two considerations: i) the user’s requirements have to be fulfilled and ii) all components should be based on proven technologies in order to minimize the developmental efforts and any technological risk.

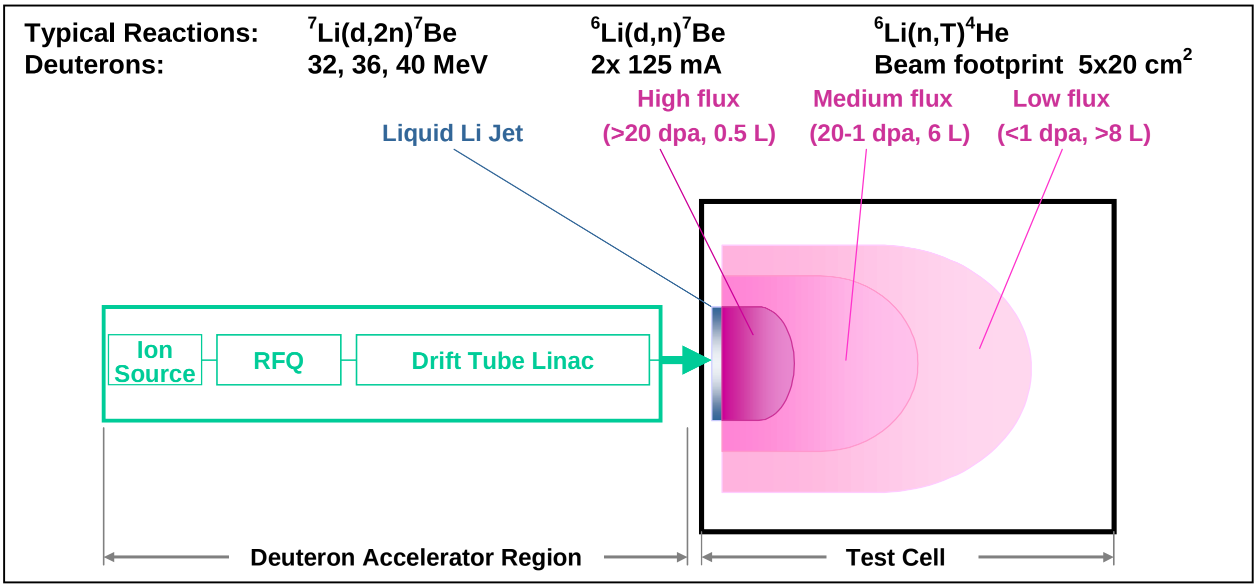

Fig. 1: Schematic layout of the D-Li stripping-type neutron source.

In Fig. 1 the principle of this design concept is given. IFMIF is a high intensity neutron source driven by two 40 MeV deuteron cw linear accelerators with 125 mA beam current each striking a single thick flowing lithium target under 20° impinging angle producing neutrons by several nuclear reactions with a broad maximum peaked at 14.6 MeV The neutrons are mainly collided in forward direction. Alternatively 30 and 35 MeV deuterons can be produced. Parameter analyses of the fluid flow and the nuclear response of the target and the test assembly have led to the selection of a beam footprint of 20 cm wide by 5 cm high. This relatively large area reduces the heat and particle flux density in the liquid lithium and gives favorable volumes and dimensions with regard to the test cell and it's accessibility for different flux regions. The test cell itself can be divided in zones with different flux levels. The achievable volumes for the different zones are indicated in Fig. 1 together with the minimum annual displacement levels.

3. SUITABILITY CRITERIA

The requirements for testing in IFMIF are primarily governed by structural materials demands and have been formulated for the first time at the workshop in San Diego in 1989 [3]. They are summarized in Tab.1. These initial requirements consist mainly of a definition of the minimum volume necessary to perform manifold experiments for a mean neutron wall loading of 2 MW/m^2 up to lifetime fluence levels. In addition the neutron energy spectrum should meet that of a fusion reactor as near as possible and the allowable neutron flux gradients should not be large compared to the critical dimension of specific specimen geometries. Finally the machine availability and the time structure of the neutron source have to be adequate. These suitability criteria have been elaborated further by the users group and were recently discussed in more detail in ref [7]. During the past few years besides technical improvements significant progress has been achieved in the characterization of the neutron response and with regard to a comprehensive evaluation of relevant damage parameters.

Table 1: Requirements for an Intense Neutron Source (IEA-Workshop in San Diego 1989).

1. Neutron flux/volume relation:	Equivalent to 2MW/m^2 in 10 liter volume (1 MWy/m^2 $\cong$ 10 dpa$_{NRT}$)
2. Neutron spectrum:	Should meet first wall neutron spectrum as near as possible; criteria are: - Displacements damage (DPA), - Primary recoil spectrum (PKA), and - Important transmutation reactions (He, H)
3. Neutron fluence accumulation:	Demo-relevant fluence of 150 dpa$_{NRT}$ in few years
4. Neutron flux gradient:	≤10%/cm based on minimum dimensions of CT- and Charpy-V specimen
5. Machine availability:	70%
6. Time structure:	Quasi continuous operation

Neutrons of a D-Li source show an energy distribution around a peak flux position that can be adapted to the 14 MeV neutron peak of a typical D-T fusion spectrum by an appropriate choice of the deuteron energy. Using the reference design with 40 MeV, the peak flux of uncollided IFMIF neutrons is between 14 and 15 MeV. The question, whether the "high energetic tail" beyond 14 MeV is a matter of concern with respect to the suitability of IFMIF, was subject of continuous discussions and needed a critical evaluation with regard to several physically relevant irradiation parameters. The parameters evaluated so far rely on Fe as major constituent of steels and include (i) displacement cross sections and derived quantities like displacement damage rates or time integrated damage doses, (ii) production cross sections for important transmutants like He and hydrogen isotope generation rates, (iii) flux gradients for neutrons and irradiation parameters, and (iv) engineering responses like nuclear heating rates. For all these parameters detailed spatial distributions have been calculated for the high (table 2), medium and low flux test modules using the MCNP Monte Carlo Code with newly developed neutron source models, extended data libraries and detailed three-dimensional geometrical models. An important outcome of these and other calculations is that in spite of the high energy tail of IFMIF neutrons all reactor-relevant irradiation parameters like He/dpa rate, H/dpa rate or recoil energy distribution are closely represented by IFMIF. E.g., within the high flux volume of IFMIF, the dpa and transmutation rates can be higher by a factor of 2-3 compared to DEMO conditions, but the important ratios of gas production to dpa are nearly identical. This gives the possibility for accelerated testing and therefore allows a much faster material development, because an anticipated life-time dose of 150-200 dpa can be achieved for selected key parameters within a few years.

Table 2: Comparison of the IFMIF high flux test module (HFTM) with outboard blankets of ITER and DEMO. All calculations are performed with MCNP code and extended nuclear data libraries for collided neutrons in iron [8].

Irradiation parameter	IFMIF HFTM*	ITER	DEMO
Total neutron flux [n/(s cm^2)]	4 x 10^{14} - 10^{15}	4 x 10^{14}	7.1 x 10^{14}
Hydrogen production [appm/FPY]	1000 - 2500	445	780
Helium production [appm/FPY]	250 - 600	114	198
Displacement production [DPA/FPY]	20 - 55	10	19
H/DPA ratio [appm/DPA]	35 - 50	44.5	41
He/DPA ratio [appm/DPA]	9.5 - 12.5	11.4	10.4
Nuclear heating [W/cm^3]	30 - 55	10	22
Wall load [MW/m^2]	3 - 8	1.0	2.2

* dependent on the exact position inside the HFTM

For a more quantitative evaluation of the effects of displacements on different radiation damage phenomena, the energy transferred to a target atom, that is the recoil spectrum of the primary-knocked-on atom (PKA), was analyzed further [7,9]. Within that context it has been shown that the probability function *W(T)* which describes the fraction of displacement damage energy produced by PKA-atoms as a function of their kinetic energy, is similar for IFMIF and DEMO. This is a direct indication that IFMIF closely reflects both, the single defect and the cascade production rates of D-T fusion neutrons.

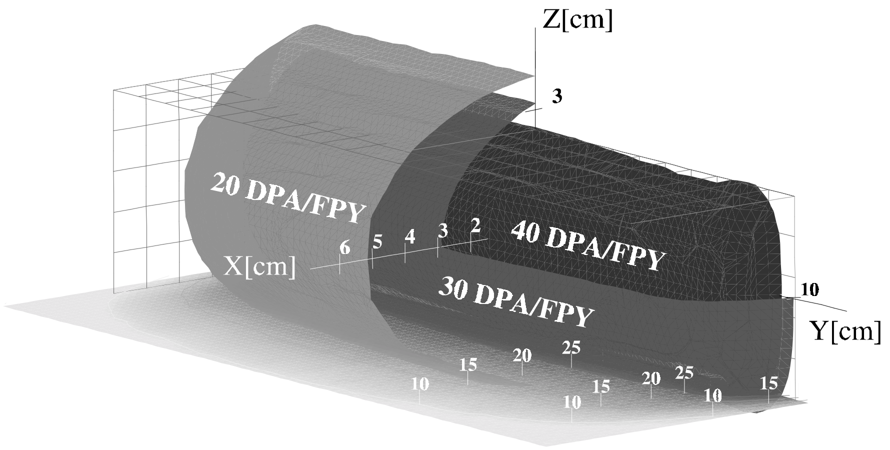

Fig. 2: Volume to DPA/FPY relation for Fe [8,9]. The iso-surfaces envelop a volume of 590 cm^2 for >20 DPA/FPY, 264 cm^3 for >30 DPA/FPY and 110 cm^3 for >40 DPA/FPY.

During the optimization procedure of IFMIF the criterion of reasonable volume/flux relations with minimum flux gradients had highest priority. After a series of optimization calculations it was clear that a beam footprint of 5x20 cm^2 would satisfy properly these requirements. In order to evaluate whether the limited high flux test volume of 0.5 liter is adequate to obtain the necessary materials property data, based on a set of seven types of specimens with „baseline“ geometries, detailed test matrices have been elaborated for the high flux test region of IFMIF. The evaluations have shown that with such miniaturized specimens the relatively small volume of the high-flux region can be equipped with instrumented rigs accommodating many hundreds of specimens and therefore is adequate to obtain within a 15-20 years program for various first wall and blanket structural materials up to about 150 dpa major parameters of an engineering database. That is, using vertical supported test modules and on the basis of small specimen test technologies, IFMIF is suitable of providing sufficient volume and appropriate irradiation environments to meet the requirements defined by the users community. Fig. 2 shows flux/volume contours and total available irradiation volumes within the high flux test zone calculated with the reference design [8,9]. The development of standardized small specimens does not only greatly reduce the minimum irradiation volume, but also reduces the flux gradients inside the specimens to less than 10% and thus guarantees a quasi-homogeneous irradiation at any position in the test module.

4. FACILITY DESCRIPTION

The IFMIF project is organized into the five subsystems (1) accelerator facilities to produce and transport accelerated deuterons, (2) target facilities which provide a flowing lithium jet to convert the deuterons into neutrons, (3) test facilities to irradiate, handle and examine specimens, (4) conventional facilities, and (5) central control system and common Instrumentation (fig. 3). The two parallel accelerators, each approximately 50 m long, produce a beam which is turned through approximately 90 degrees where it is directed to one of the liquid lithium targets where the two beams overlap. The totally overlapping beam footprint on the Li-target has significant advantages during off-normal operation of either beam, because it is unlikely that both accelerators shows flux perturbations or will go down by the same time. If only one accelerator system fails for a shorter period, the test modules continues being irradiated. The IFMIF reference design provides two independent test cells; that is, the beams can be directed to either one of the Li-targets. The accelerator systems along with the Li-loop (which feeds the targets) and the test cells are located below ground level, whereas major power systems and hot cell facilities are located at ground level. Because of the level of uncertainty in the amount of testing and development needed to characterize the damage effect of 14 MeV neutrons, the IFMIF facility has been designed from the outset to accommodate two additional accelerators, so that both test cells could be served simultaneously. Major engineering efforts have been undertaken to establish for all subsystems a design that is based on available and already proven technologies. The developed reference design includes extensive reliability, availability, maintainability as well as safety studies and is conceived for long-term operation with a total annual facility availability of at least 70%.

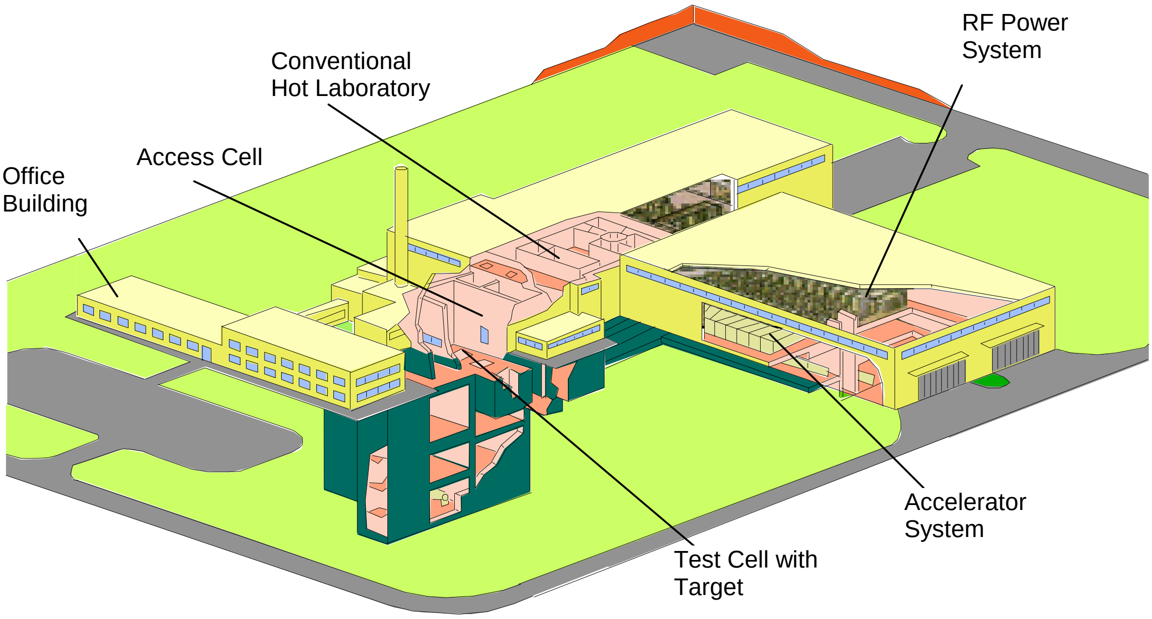

Fig. 3: 3-dimensional view of IFMIF

4.1 Test Facilities

As shown in figure 4, the two D-beams are focused in the Test Cell on the liquid lithium target with a 20 degree angle, producing neutrons that are mainly collided in forward direction. The IFMIF

Test Cell contains (1) two vertically oriented test assemblies, referred to as Vertical Test Assemblies (VTAs) 1 and 2, which support the test modules used for long-term irradiation of specimens in the high and medium flux regions, (2) an array of tubes, referred to as Vertical Irradiation Tubes (VITs), used for inserting test capsules in the low and very low flux regions, (3) a vacuum liner that encloses the test modules and also accommodates the lithium target, (4) a heat shield surrounding the liner to protect the concrete neutron shielding from overheating, (5) the Test Cell Removable Cover, which can be lifted with an overhead crane to gain access to the entire Test Cell, and (6) a seal plate for providing a vacuum seal between the removable vertical test assemblies and the Removable Cover.

The three Vertical Test Assemblies considered in the present design are sufficient for the four flux regimes. The test module of the VTA1 is devoted essentially to the development and qualification of structural materials by irradiating simultaneously hundreds of miniaturized specimens. At present in IEA-coordinated, collaborative materials programs the three leading candidates for structural materials are considered to be ferritic/martensitic steels, vanadium alloys, and eventually SiC/SiC composites. In addition, some space of the high flux test region is reserved for a limited number of unspecified alternative materials. Most of the structural materials will be irradiated in the high flux region followed by post irradiation examinations in hot cells. More sophisticated in-situ experiments are in some cases mandatory for measuring the materials properly. Therefore, simultaneous in-situ push-pull creep fatigue tests and in-situ tritium release tests on various breeder materials are foreseen in the medium flux region. Complete test module designs have been elaborated meanwhile also for such type of experiments. In the present IFMIF reference design the high and medium flux test modules are cooled by low pressure helium gas. The low and very low flux regions are equipped with the VIT system that allows the irradiation of special purpose materials down to cryogenic temperatures.

The Access Cell is located directly above the Test Cells and contains beside the helium gas coolant loops for VTAs various remote handling equipment like telescopic master/slave manipulators and a universal robotic system. The present design concept implies that after disassembling all irradiated specimens and materials of interest will be investigated in suitable Post-Irradiation Examination (PIE) Facilities at IFMIF site. The PIE Facilities dedicated to the users for qualified analyses include (i) the PIE Laboratory, for mechanical testing of conventional, nontritiated high level radioactive specimens, (ii) Shielded Glove Box Laboratory for microstructural analyses as well as (iii) the Tritium Laboratory for the investigation of tritium contaminated or tritium containing specimens and components.

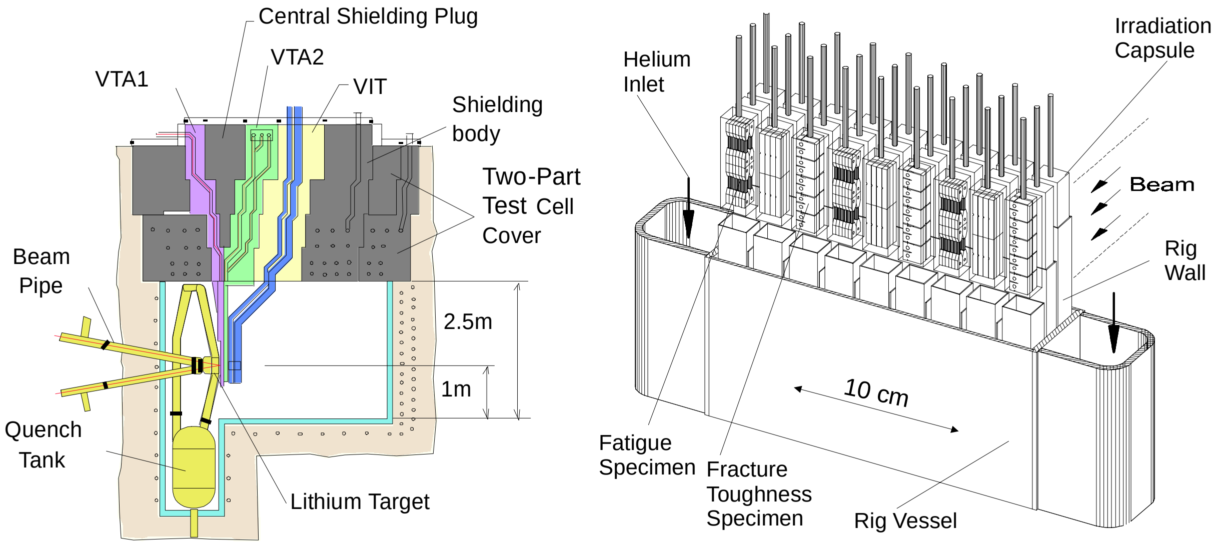

Fig. 4: Elevation view of the Test Cell (left) and section view of the high flux test module (right) with several hundreds of specimens accommodated in instrumented capsules and rigs.

4.2 Lithium Target System

The lithium target system consists of two main components: the target assembly and the lithium loop. The former provides a stable lithium jet in order to produce the neutrons, while the latter circulates the lithium and removes the heat deposited by the deuteron beams. The main requirements of the target system are as follows: (i) Removal of about 10 MW of deuteron beam power by using a high velocity lithium jet. The jet should have a stable free surface and boiling must be prevented within the beam foot print in order to provide a firm neutron field. (ii) Control of the impurity level (T; ^{7}Be for the radiological safety; C, O, N for the materials compatibility) in the lithium loop system, (iii) provide safety margins with respect to lithium hazard and tritium release from the lithium loop system, and (iv) achievement of a system availability of more than 95% during the lifetime of the plant. This loop also contains systems for maintaining the high purity of the loop required for radiological safety and for minimizing corrosion of the loop structure by the hot flowing lithium. The total lithium inventory is 21 m^3. Based upon a thorough assessment of various target designs, a modified FMIT-type target with a replaceable backwall has been selected for the baseline design. The replaceable backwall is bolted to the back site of the target assembly. Seals around the edges are foreseen to maintain different vacuum conditions in the target chamber (10^{-3} Pa) and in the test cell (~10^{-1} Pa). The target assembly, with the exception of the replaceable backwall, is designed to withstand long-term neutron exposure.

During the CDE phase significant improvements [8,10,11] of the conceptual design have been made that include (i) an optimization of the overall system design, (ii) extended thermo-hydraulic calculations to assess the Li jet stability under different conditions, (iii) a probabilistic evaluation of accident sequences showing very low values for potential accident probabilities, and (iv) a detailed outline of lithium purification and on-line monitor systems.

4.3 Accelerator Facilities

The IFMIF requirement for 250 mA of deuteron beam current delivered to the target will be met by two 125-mA, 40-MeV accelerator modules operating in parallel. This technological approach is conservative with respect to the current capabilities of rf linac technology and provides operational redundancy by allowing operation to continue at 125 mA when one or the other of the two accelerators is temporarily removed from service for repair. The IFMIF deuteron comprises a sequence of acceleration and beam transport stages. The ion source generates a cw 140-mA deuteron beam at 100 keV followed by Low Energy Beam Transport (LEBT) that guides the deuteron beam from the operating source to a Radio Frequency Quadrupole (RFQ) Accelerator. The RFQ bunches the beam and accelerates 125 mA to 8 MeV. The 8 MeV RFQ beam is injected directly into a room-temperature, Drift-Tube-Linac (DTL) of the conventional Alvarez type with post couplers, where it is accelerated to 32, 36, or 40 MeV. The rf power system for the IFMIF accelerator is based on a tetrode amplifier operated at a power level of 1.0 MW and a frequency of 175 MHz. Operation of both the RFQ and the DTL at the same relatively low frequency is a conservative approach for delivering the high current deuteron beam with low beam loss in the accelerator. The use of only one rf frequency also provides some operational simplification. Although beam transport calculations have shown fairly low deuteron beam losses, thus allowing “hands-on” maintenance, the accelerator facility will be designed in such a way that remote maintenance is not precluded.

With respect to high current cw accelerator experience, the IFMIF project presently gains also from relevant results in other accelerator projects. E.g. at the University of Frankfurt a 200 mA cw 94% proton beam (corresponds by scaling to 140 mA deuterons) was extracted in July 1998 through a 8 mm aperture, and also at CEA-Sacley a 126 mA cw proton beam was transported recently through a 10 mm aperture for a long operation time with 96% availability. Finally, within a US program, a 100 mA cw proton linac prototype to about 10 MeV is under construction. For the IFMIF project these results and improvements are highly significant, because the experimental data strongly validate the predictions from the codes, greatly increasing confidence that the reference IFMIF design objectives are realistic and can be met largely with available technology [8,12-14].

5. SUMMARY

Significant progress has been achieved during the past few years in establishing for the fusion materials community a suitable and feasible concept for an accelerator-based intense D-Li neutron source that produces neutrons with a suitable energy spectrum at high intensity and sufficient irradiation volume to perform all necessary kinds of tests. IFMIF essentially fulfills all requirements for the users. That is, it adapts the physically based damage parameters like dpa, PKA-spectra and transmutations reasonably well to D-T-fusion neutrons, and also has sufficient capacity to perform all necessary types of experiments for the development and qualification of structural, breeding and other materials. This can be achieved by using well proven miniaturized specimen test technologies. An attractive feature of IFMIF is the capability to perform in a limited volume accelerated irradiations up to about 55 dpa/FPY. Major engineering efforts have been undertaken to establish a test cell design that allows safe and completely remote controlled handling of vertical test assemblies and test modules. The developed IFMIF reference design includes detailed reliability, availability, maintainability as well as safety studies and is conceived from the early beginning for long-term operation with a total annual facility availability of at least 70%. Compared to many other proposals, this facility is based on available and largely proven technologies. From a technical viewpoint IFMIF could be built at low technological risk within half a decade after a short EDA phase, presupposed that approval would come soon. There are many reasons to discuss now within the Fusion Community the priority for such a facility.

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