Recent Advances at the International Fusion Materials Irradiation Facility IFMIF

A. Möslang 1), U. Fischer 1), V. Heinzel 1), P. Vladimirov 1), R. Ferdinand 2), H. Klein 3), B. Riccardi 4), M. Gasparotto 5), H. Matsui 6), M. Ida 7), H. Nakamura 7), M. Seki 7), M. Sugimoto 7), H. Takeuchi 7), T. Yutani 7), T. Muroga 8), R.A. Jameson 9), T. Myers 10), J. Rathke 10), T.E. Shannon 11), S. Païdassi 12), V. Chernov 13)

1) Forschungszentrum Karlsruhe GmbH (FZK), IMF-I, P.O. Box 3640, 76021 Karlsruhe, Germany
2) Commissariat a l'Energie Atomique (CEA) Saclay, Bat. 706, 91191 Gif-sur-Yvette, France
3) Johann Wolfgang Goethe University, IAP, 60054 Frankfurt am Main, Germany
4) Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA), 00044 Frascati, Italy
5) EFDA Close Support Unit Garching, Boltzmannstr. 2, 85748 Garching, Germany
6) Tohoku University, Institute for Materials Research, Sendai 980-8577, Japan
7) Japan Atomic Energy Institute (JAERI), Tokai-mura, Ibaraki-ken 319-1195, Japan
8) National Institute for Fusion Science (NIFS), 322-6 Oroshi, Tokai Gifu 509-5292, Japan
9) Los Alamos National Laboratory (LANL) LANL, Los Alamos, NM 87545, USA
10) Advanced Energy Systems, 27 Indust. Blvd. Unit E, Medford, New York 11763, USA
11) University of Tennessee, Knoxville, TN 37996-2210, USA
12) Commission of the European Communities, 1049 Brussels, Belgium
13) State Science Center RF, VNIINM, P.O. Box 369, 123060 Moscow, Russia

E-mail contact of the main author: anton.moeslang@imf.fzk.de

Abstract. As the qualification of materials under fusion-specific conditions is inevitable for the design, performance, and safe operation of fusion power reactors, timely availability of a suitable intense neutron source has become a major element in fusion strategy scenarios. In response to this need ,a basic design for the accelerator-driven International Fusion Materials Irradiation Facility (IFMIF) has been developed under the umbrella of the IEA's Executive Committee on Fusion Materials within the "Conceptual Design Activity" phase (1995-96). This design was modified substantially during the "Conceptual Design Evaluation" phase (1997-98) and in 1999, mainly to meet global requirements of cost reduction. The main objectives of the current "Key Element Technology" phase (2000-2002) are to reduce any technology risk factors and to verify relevant component designs on a laboratory scale. A major result from recent neutron transport calculations and targeted design optimizations is that the high-flux test volume could be increased by ~20% and that for structural materials fusion reactor-relevant irradiation parameters like the H/dpa rate, He/ dpa rate or recoil energy distribution are perfectly represented by IFMIF over the entire test volumes. Significant progress in accelerator systems includes 1000 h continuous operation of an intense D^+ source, detailed beam dynamics design by separate groups verifying IFMIF performance, and reliability tests of a diacrode RF power amplifier at 1 MW for 1000 h. With respect to the lithium-target area, substantial advances have been made during the KEP phase, including a detailed integral design based on well-founded thermohydraulic analyses and various experiments on existing loops dedicated to impurities and potential corrosion issues. Preparations are presently made to enter an "Engineering Validation and Engineering Design Activity" (EVEDA) phase that includes the experimental verification of major subsystems operation as well as the establishing of an engineering design for licensing and construction.

1. Introduction

The long-term development towards fusion DEMO reactors or PROTOTYPE power plants aims at obtaining materials that can withstand high neutron wall loading and heat fluxes for sufficiently high neutron fluences of at least 10-15 MWy/m^2. At present, an appropriate materials testing facility which could adequately simulate this fusion environment is not available, although its need has been recognized on several occasions [1-6], including the Fusion Fast Track Experts Meeting convened on the initiative of the President of the EU Research Council and chaired by Prof. D. King [7]. During the international selection process of a feasible, reliable, and near-term intense fusion neutron source, the mission of such a facility has been defined as follows: (i) Qualification of candidate materials up to the full lifetime of anticipated use in a fusion DEMO reactor, (ii) calibration and validation of data generated from fission reactors, particle accelerators, and other neutron devices, and (iii) identification of possible new phenomena which might occur due to the fusion neutron exposure. Altogether, a broad international consensus has been reached meanwhile, according to which a suitable intense neutron source is inevitable for the construction of a DEMO-type fusion reactor and that the accelerator-driven International Fusion Materials Irradiation Facility (IFMIF) is the best choice with the potential to fulfil the requirements within a realistic time scale.

In a joint effort of the European Union, Japan, and the United States of America, with the Russian Federation as an associated member, and under the auspice of the IEA, a reference conceptual design [8] and a detailed cost estimate [9] were elaborated for IFMIF during the "Conceptual Design Activity" phase (1995-96). The design developed was the basis for the "Conceptual Design Evaluation" phase (1997-98) and a subsequent design reconsideration (1999) that focused on cost reduction [10] and preliminary facility deployment strategies [11].

In 2000, a 3-year "Key Element Technology Phase" (KEP) was initiated with the objective of reducing some key technology risk factors which are needed to achieve a CW deuterium beam with the desired current in the accelerators, to verify relevant component designs on a laboratory scale both in the Li-target system and test cell system, and to validate design codes. Therefore, 83 proposed KEP tasks are being processed on a voluntary basis by the EU, Japan, USA, and Russia. This paper presents KEP achievements in the major areas of accelerator system, lithium target system, and test cell system. Finally, we summarize future plans and the implementation of an "Engineering Validation and Engineering Design Activity" (EVEDA) phase that includes experimental verification of major subsystems (endurance and remote handling tests) as well as the establishing of engineering data for licensing and construction.

2. Recent Advances

2.1 IFMIF Outline and Design

IFMIF is a high-intensity neutron source driven by two 40 MeV deuteron continuous-wave (CW) linear accelerators each with 125 mA beam current striking a single thick, flowing Li target under a 20 degree impinging angle, thus producing neutrons by nuclear reactions with a broad maximum peaked at 14-16 MeV. As the neutrons produced within the common beam footprint of 5x20 cm^2 are mainly collided in forward direction, the test modules housing the specimens to be irradiated are positioned immediately adjacent of the Li target.

The main components of IFMIF have been classified into five subsystems: (1) Accelerator Facility which produces accelerated deuterons, (2) Target Facility which produces a stable flowing lithium jet to convert the deuterons into neutrons, (3) Test Facilities which expose, handle, and examine specimens, (4) Conventional Facilities, and (5) the Central Control System and Common Instrumentation. Figure 1 shows a bird's eye view of the cost-reduced IFMIF project. To meet the cost reduction requirements, various design simplifications have been made but a potential upgrading to 4x125 mA beam current is now no longer possible. Major engineering efforts have been undertaken to establish a design that is based on largely available and proven technologies. The design developed is based on extensive reliability, availability, maintainability, and safety studies and is conceived for long-term operation with a total facility availability of at least 70%.

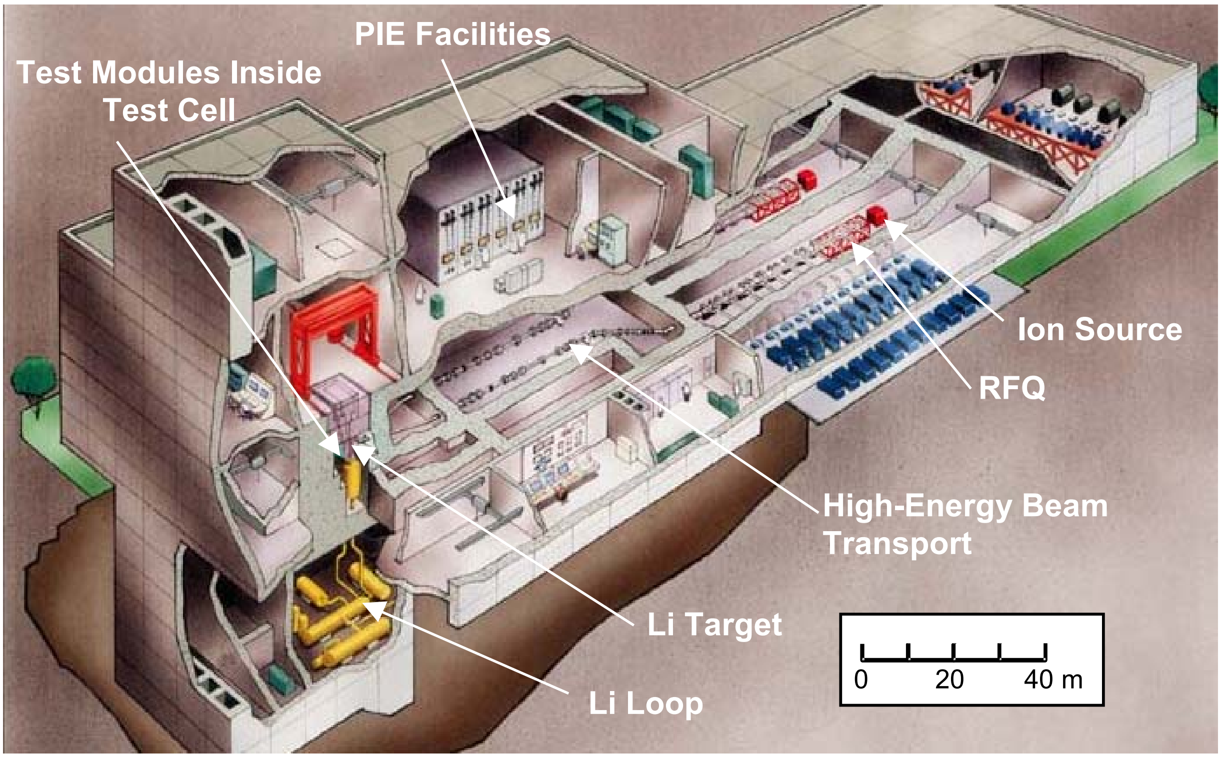

FIG. 1: Overview of the present IFMIF design with major subsystems. The lithium target which converts deuterons into neutrons and all test modules which accommodate the specimens are located in a common test cell. The Post-Irradiation Examination (PIE) facilities are foreseen to examine irradiated specimens. Maximum availability is achieved by two completely independent accelerator lines; the ion source, RFQ and HEBT of one deuteron beam line are indicated.

During the past few years, substantial design improvements were made especially in buildings and utilities as well as in tasks related to the safety assessment for occupational radiation exposure (ORE). The site area including the main building (Figure 1), electrical switchyards, administration buildings, utilities, etc. is about 250 m x 200 m, and the required total power will be 50 MW including emergency power. The main building has an area of 170 m x 60 m, a maximum height of 26 m, and a maximum depth of 11 m. Substantial design improvements have also been achieved (i) for the tritium laboratory, (ii) the access cell above the test cell, which houses all remote-controlled tools for any assembly and maintenance operations in the test cell, and (iii) the complex heating, ventilation, and air conditioning system. With the ORE assessment and the "reliability, availability, and maintainability" tasks progressing continuously, key radiation protection issues were identified, further design improvements accomplished, and international radiation protection practices reviewed, thus providing suitable benchmarks for individual and collective doses for compliance with the ALARA requirements and development of workers' radiation protection guidelines.

2.2 Accelerator System

The IFMIF requirement of 250 mA of deuteron beam current delivered to the lithium target will be met by two 125-mA, 40-MeV accelerator modules operating in parallel. Although the present reference design is largely based on conventional, room-temperature, and rf linear accelerator (rf linac) technologies, more advanced accelerator technologies like superconducting linacs that have the potential of reaching an even higher performance are also being investigated. This technological approach of the reference design selected is only cautiously aggressive with respect to the current capabilities of the rf linac technology and provides operational redundancy by allowing operation to continue at 125-mA when any of the two accelerators is temporarily removed from service for repair. Each 125-mA accelerator is designed with sufficient derating, but not with a significant upgrade capability. The IFMIF deuteron accelerator shown in Figure 1 comprises a sequence of acceleration and beam transport stages. A cw 155-mA deuteron beam is extracted from the ion source at 95 keV. A low energy beam transport (LEBT) guides the deuteron beam from the source to a radio frequency quadrupole RFQ. The RFQ bunches the beam and accelerates 125 mA to 5 MeV [10]. The 5-MeV RFQ beam is injected directly into a room temperature, ramped-gradient Drift Tube Linac (DTL) of the conventional Alvarez type with post couplers, where it is accelerated to 40 MeV. The baseline rf power system for the IFMIF accelerator assumes the use of diacrode technology with an output 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 to delivering the high-current deuteron beam with low beam loss in the accelerator. This will facilitate hands-on maintainability without remote manipulators.

Ion injector: The IFMIF ion injector, has to provide excellent beam quality, sufficiently high beam current, and high operational availability. To minimize downtime and maximize system availability, all failure-prone injector components are being designed for rapid exchange in the accelerator vault, subsequent to shutdown. The injector for IFMIF will consist of an ion source of either the ECR or volume type and the LEBT to the RFQ. Rapid progress is currently being reached for the different source type options. The ion source highlights include (i) parallel testing of three ion source candidates using the same beam extraction system and instrumentation at JAERI and (ii) injector operation with a D^+ beam at CEA Saclay, showing that IFMIF beam performance requirements can be achieved. 1000 h reliability runs are underway. Although the ECR source has already shown the required performance, a lot of activities are being undertaken to continuously improve source availability [13].

RFQ accelerator: The output energy 5 MeV was selected, because it is the lowest energy allowing a F0D0 magnetic lattice in the DTL which is desirable for halo control and the consequent minimization of beam loss. The high output energy, however, necessitates a long RFQ structure of 12.5 m. The RFQ will need approximately 3 diacrodes of 1 MW each. Within the present KEP phase, the design of the RFQ beam dynamics has been finished. The output beam current met the 125mA goal. Beam emittance in both the longitudinal and traverse plane was optimised for the DTL. Good progress was made in the tuning process of a 4-vanes RFQ based on a 6 m long cold model. In addition a 4-rod RFQ is under consideration [14].

DTL: The IFMIF reference design includes 5 DTL tanks with a peak accelerating field of 1.75 MV/m and 9 rf tubes to power them. Comprehensive particle dynamics calculations have been performed for an Alvarez type DTL from 5 to 40 MeV, showing that for various conditions stable solutions with low emittance growth and full transmission could be found. The DTL beam dynamics design released has no particle losses. The same is true for a superconducting alternative, using the new CH-structure [15]. In case of superconductivity the required cw operation is easy to achieve, the rf losses are lower and the linac is shorter and has larger apertures [16].

RF tube development: Outstanding progress has been made in developing and testing a new kind of gridded tube called diacrode which can overcome the limitations of conventional tetrodes, mainly the RF losses, by a factor of 4. The challenging goal was to meet reliability requirements of IFMIF, namely, 1000 h at 1MW cw rf power and 175-200 MHz. Very recently, endurance tests with a TH 628 Diacrode have been performed for the first time over 1047 hours at full power in the range of 1010-1030 kW cw rf and 200 MHz, thus showing the capability to operate entirely stably under IFMIF-relevant conditions.

2.3 Target System

The Li target system consists of the target assembly and the Li loop [12]. The design requirements of the Li target system are (i) heat removal from the deuterium beams that produce the intense neutrons flux, (ii) control of the impurities remaining below permissible levels to ensure safety with respect to the Li hazard and tritium release from the Li loop, and (iii) achievement of a system availability of more than 95% during the lifetime of the plant. To remove the extremely high heat deposition of 10 MW within a beam footprint of 5 cm x 20 cm, the liquid Li jet in the target station has a velocity of ~15 m/s, a flow rate of 130 l/s, and an inlet temperature of 250 °C. Fig. 2 shows a bird's eye view of the improved design of the lithium target system with major subsystems.

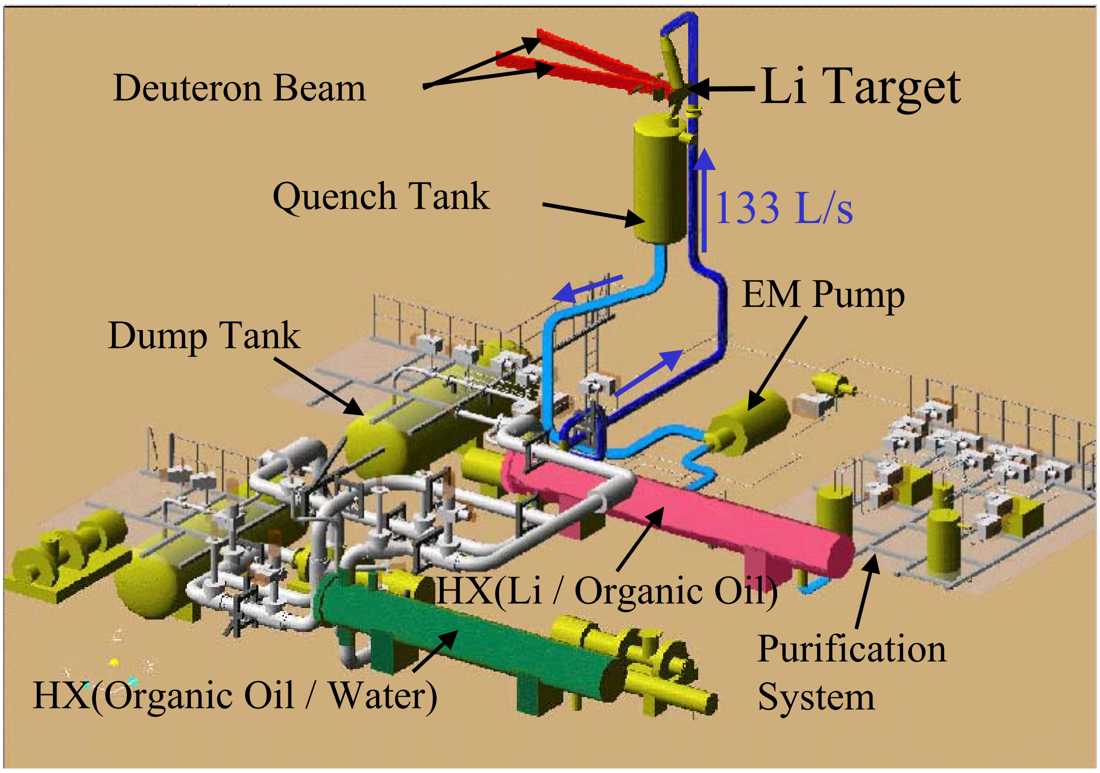

FIG. 2: Bird's eye view of the lithium target system

Target assembly and Li loop: The Li loop circulates the Li to and from the target assembly through the Li purification and heat exchange systems by an electromagnetic pump. The Li target assembly consists of a flow straightener, a reducer nozzle, a back wall, drain baffles, and flanges. The material of the target assembly is stainless steel except for the back wall which is made of a reduced-activation ferritic/martensitic steel. The flow straightener is aimed at changing the turbulent flow to a laminar one. Extensive 3D thermohydraulic and fluid dynamics calculations have been performed during the present KEP to further improve the Li jet performance by targeted design modifications. Due to the centrifugal force of 160 G induced by the curved back wall, the maximum temperature in the Li jet could be kept at 400 °C which is well below the local boiling temperature of 1090 °C. To validate the calculations and the double reducer nozzle concept, a Li jet flow experiment has been started. Based on industrial experience, great progress has been achieved in designing an advanced remote handling system for the entire target assembly. A unified universal robot system (mobile crane above the test cell in Fig. 1) can be equipped with various tools in order to perform all maintenance and assembly/disassembly operations of any modules inside the test cell.

Li purification system: Major impurities in the Li loop are protium, deuterium, tritium, ^{7}Be, and other elements like C, N, and O. Typical isotopes produced by direct reactions of the deuterium beam with the Li are T and ^{7}Be. Deuterium from the beam is also contained in the Li flow. At full power operation, the total production rates of H, D, and T are calculated to be about 5 g/year, 160 g/year, and 7 g/year, respectively. In the present design the Li purification system consists of various monitors, a cold trap, a V-10%Ti (and/or Cr) hot trap, and an yttrium hot trap. Without removal of ^{7}Be, the activation level would saturate at 140 kCi. Although ^{7}Be can be removed effectively by the cold trap at 200 °C, some ^{7}Be will remain inside the loop so that a remote handling system is needed for maintenance. Mainly due to an effective erosion/corrosion prevention and to avoid deterioration of the Y-hot-trap, maximum impurity concentrations of ~10 wppm/species have been determined for C, N, and O.

2.4 Test Cell System

As described in more detail [8], the IFMIF test cell and specimen testing areas must be capable of accommodating the wide range of environments associated with fusion reactor materials. According to these materials testing needs, the irradiation volume downstream of the neutron-producing Li target has been partitioned into a high-flux region with a displacement damage accumulation of about 20-55 dpa/ full power year (fpy) and an available volume of 0.5 L, a medium-flux region (1-20 dpa/fpy, 6 L), and a low-flux region (<1 dpa/fpy, >100 L). All test modules used for the different flux zones have to be instrumented and able to control the irradiation temperature that might vary from 250 to 1000 °C in the high-flux and medium-flux regions down to cryogenic temperatures in the low-flux zones. Hot cells will be necessary for periodic maintenance of activated devices and complete post-irradiation examination (PIE) of all irradiated specimens and mock-ups. Fig. 3a shows an outline of the revised test cell design. The high-flux test module of the vertical test assembly 1 (VTA1) is devoted to high-fluence irradiation of candidate structural materials, the 2 medium-flux test modules of VTA2 are dedicated to more sophisticated in situ experiments like creep fatigue tests or T release tests on breeder ceramics, while the vertical irradiation tube system (VIT) allows the irradiation of special purpose materials in the low-flux region. As the limited irradiation volume of any accelerator-based neutron source is a restriction, use of miniaturized specimens is mandatory for the high flux region. Rapid progress is being made in the international materials community in developing a set of miniaturized specimens with proven scaling laws. The development of online subminiature fission chambers for a quantitative determination of local neutron/gamma spectra inside the IFMIF test modules is in the final stage.

D-Li source term and nuclear data above 20 MeV: An important step forwards has been done in the simulation of the neutron production of the D-Li source using the Li(d,xn) reaction cross sections from evaluated data files. In order to further significantly reduce the remaining n-source yield uncertainty of ±20%, dedicated "time of flight" experiments are being performed with neutrons generated by 20-40 MeV deuterons striking a Li-target. Over the KEP period, substantial efforts have been devoted to preparing and releasing an intermediate energy activation file (IEAF) with 679 target nuclides from Z=1 to 84 with approximately 51000 excitation functions. On the basis of this library IEAF-2001 and the recent ALARA activation code, reliable activation analyses have become available for the first time. A major outcome of initial activation analyses is that for reduced-activation steels, the dose rates after IFMIF and DEMO reactor irradiation are comparable for equivalent neutron fluences.

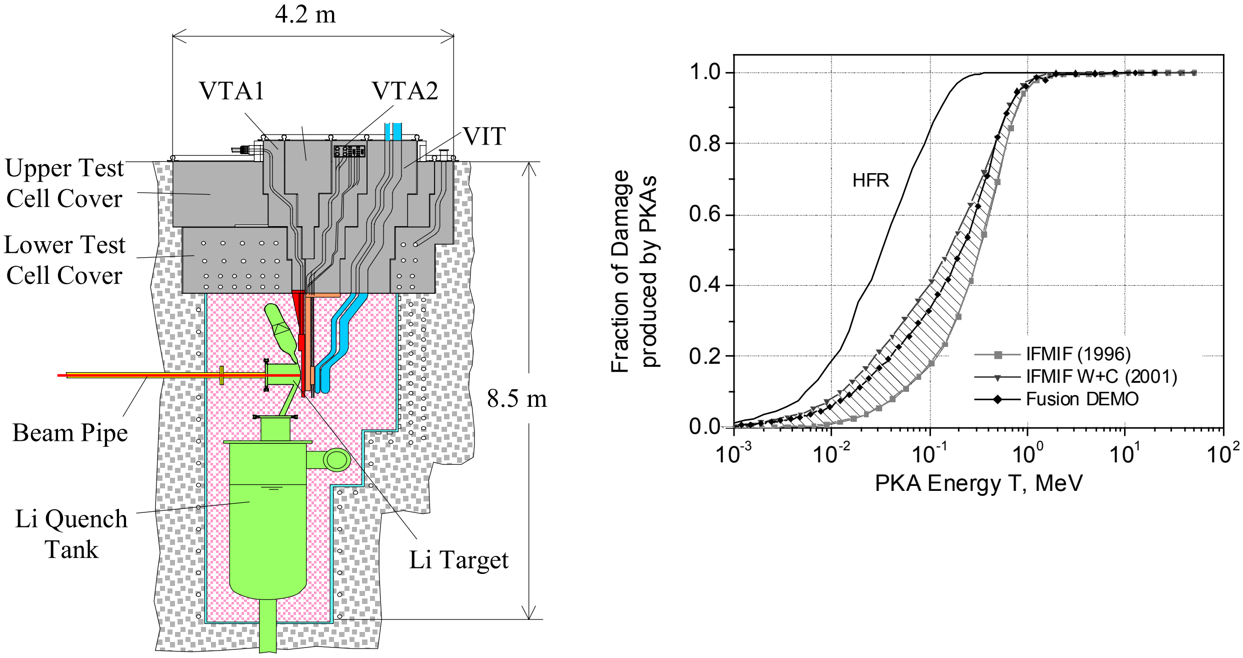

Fig. 3: Elevation view of the test cell (left) and recoil energy distribution functions for the medium-flux volume of IFMIF (hatched area), a typical blanket of a fusion DEMO reactor, and for the mixed spectrum reactor HFR Petten (right).

Test modules VTA1 and VTA2: Within the last two years, irradiation performance in both the high-flux and medium-flux test modules could be further improved significantly on the basis of the above-mentioned nuclear data libraries and advanced neutron transport calculations. A major result of these calculations is that the shape of the IFMIF neutron spectrum now follows that of a DEMO reactor breeding blanket over several orders of magnitude, if the test modules are surrounded with a proper combination of tungsten, graphite, and reduced-activation steel. Tungsten acts mainly as a "neutron spectral shifter" and graphite/steel as "neutron reflector". The thorough neutron transport calculations also have shown that the use of a suitable reflector increases substantially the high-flux volume by ~20%. The usual way to characterize the recoil energy (or primary knock-on atom PKA) spectrum of a radiation source is to use the cumulative damage production function which represents the fractional damage energy created by PKA recoils with energies below a given energy T. As obvious from Figure 3, DEMO-relevant conditions can be adjusted in IFMIF test modules over the entire PKA energy range. With respect to suitability criteria [17], IFMIF meets adequately DEMO reactor-relevant H, He, and dpa production rates as well as H/dpa and He/dpa ratios in structural materials like Fe-based alloys, and it can be considered a suitable test bed for ceramic breeder materials.

3. Future Plans

In order to realize IFMIF in conjunction with ITER to best meet the recognized requirements towards fusion energy development, both of these facilities being on a critical path of any approach with a reasonable time horizon, it is necessary to launch a detailed IFMIF engineering design activity in the near future. After the KEP results have been reviewed, the IF-

MIF project will be ready for a possible international decision to proceed with a ~5-year Engineering Validation and Engineering Design Activity (EVEDA) phase, during which a continuous, stable operation of the major subsystems of accelerator, target, and test facilities would be validated experimentally and a detailed engineering design and procurement specifications would be established for licensing and construction. A new specific "Annex" under the IEA Fusion Materials Implementing Agreement would be required to start EVEDA implementation around 2004. This tentative schedule and the possible subsequent IFMIF construction and operation phases towards fusion energy development have been considered by a special working group, within the IEA Fusion Materials Implementing Agreement. In the scenario considered, IFMIF operation could start about 12 years after starting EVEDA and nominal IFMIF performance could be reached about 3 years later.

Acknowledgement

Appreciation is given to all members of the international IFMIF team for their enthusiasm in developing a high performance and reliable intense fusion neutron source. Appreciation is also given to the IEA-FPCC for their continuos interest, and to many institutions and associations for their ongoing support.

References:

[1] Cottrell A. et al.; Report of the Panel on Fusion Materials Research and Testing; IEA Implementing Agreement R&D Fusion Materials, 1983.
[2] Amelincks S. et al.; "Materials for Fusion", IEA Report to the Fusion Power Co-ordinating Committee by Senior Advisory Panel, OECD/IEA (1987).
[3] Leis J.E. et al. "Report on the International Fusion Irradiation Facility", IEA Workshop, San Diego, 1989, Vol. 1: Evaluation Panel Report, pp.
[4] Airaghi A. et al.; 1999 Five-year Assessment Report Related to the Specific Programme on Nuclear Fusion, May 2000; http://www.cordis.lu/fp5/5yr_reports.htm.
[5] Lackner K. et al.; Plenary presentation on "Long-term Fusion Strategy in Europe", ICFRM-10, November 14-19 2001, Baden-Baden, Germany.
[6] Matsui H. et al.; Plenary presentation on "IFMIF Status and Perspectives", ICFRM-10, November 14-19 2001, Baden-Baden, Germany.
[7] King D.; http://europa.eu.int/comm/research/energy/gp/gp_ef_fasttrack_en.html .
[8] "IFMIF - Conceptual Design Activity Final Report"; IFMIF-CDA-Team; Ed.: M. Martone; ENEA-RT/ERG/FUS/9611-Report; December 1996.
[9] "IFMIF - Conceptual Design Activity Cost Report" ; Compiled by J.M. Rennich, ORNL/M-5502-Report, December 1996.
[10] "IFMIF Key Element Technology Phase, Reduced Cost Report"; Report JAERI-Tech 2000-014 (2000), compiled by M. Ida.
[11] H. Takeuchi et al., Fusion Energy 2000 (Proc. of 18th Internat. Conf. Sorronto, 2000).
[12] H. Nakamura et al.; Latest design of liquid Li target during KEP and future prospects in IFMIF; 22nd SOFT, 9-13 Sept. 2002, Helsinki; to be published in Fus. Eng & Design.
[13] R. Ferdinand et al., "Deuteron Beam Test For IFMIF", EPAC 2002, Paris.
[14] R. Duperrier et al., "Beams Dynamics Simulations in IFMIF Linac", EPAC 2002, Paris.
[15] A. Sauer et al., "Beam dynamics design of a superconducting 175 MHz CH-Linac for IFMIF", EPAC 2002, Paris.
[16] A. Sauer et al., "Beam dynamics layout of H-type drift tube linacs for intense light ion beams", LINAC 2002, Gyeongju, Korea.
[17] Moeslang A. et al.; Suitability and Feasibility of the International Fusion Materials Irradiation Facility (IFMIF) for Fusion Materials Studies; Nuclear Fusion Vol. 40, No. 3y, March 2000, pp. 619.