IFMIF (INTERNATIONAL FUSION MATERIALS IRRRADIATION FACILITY): A HIGH INTENSITY DEUTERON BEAM APPLICATION

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Abstract

This paper reports on the results of the Conceptual Design Activity (CDA) of the International Fusion Materials Irradiation Facility (IFMIF). IFMIF is proposed as an accelerator-based (D-Li) neutron irradiation facility to test and qualify fusion reactor materials up to end of life doses characteristic of a prototype commercial fusion reactor. Under the auspices of the International Energy Agency (IEA) an international team of specialists was set up at the end of 1994 to carry out the CDA of such a D-Li source. At the same time the minimum requirements of the facility to assure a meaningful development were defined by a Fusion Materials Expert Group.

The CDA has been carried out by individuals from institutions in Europe, Japan, the United States and Russian Federation and completed over a 2-year period (1995-96). The Design and Cost Reports covering the results of the activity were published in December 1996 [1,2]. The Fusion Power Coordinating Committee (FPCC) of the IEA expressed appreciation for the results obtained and recommended further technical studies to complete the database for an engineering design and to reduce technical risks. Owing to this a two year Conceptual Design Evaluation (CDE) phase (1997-98) has been launched supported by the same CDA team.

The main features of the facility and some recent outcomes of the CDE phase will be reported.

1 INTRODUCTION

Fusion power reactors burning DT gas mixture, release nuclear energy mainly through high energy neutrons (14 MeV). Low activation and radiation resistant materials are so needed to demonstrate their technical and economical feasibility.

On the other hand the use of materials developed for fission reactors is not advisable because the energy spectrum of fusion neutrons is different from that of fission neutrons and the related damage of materials has been demonstrated to be appreciably different.

Materials for fusion reactors must be then selected and fully qualified. For this purpose a high flux source of fusion-like neutrons, presently not existing, has to be built and operated.

The test facility suitable for such purposes has been explored through a number of international studies and workshops over the last decade.

The final criteria used for selecting the best choice among different neutron source concepts was the availability of the physics and technology required to construct and operate such a source early in the next century.

A neutron source from the Deuterium-Lithium (D-Li) stripping reaction was found to fulfil such a criteria and has been selected as the basic concept of the International Fusion Materials Irradiation Facility (IFMIF) [3,4,5,6]. The technology of accelerator based D-Li neutron source concept has been in fact developed by the Fusion Material Irradiation Test (FMIT) Project (1978-84) [7,8] and later by the Energy Selective Neutron Irradiation Test Facility (ESNIT) Program (1988-92) [9,10,11]. Major worldwide advances in accelerator technology over the past decade have further added to the credibility of this approach.

2 USER REQUIREMENTS

User minimum requirements to obtain useful irradiation data in a reasonably short operating time, indicate a test volume of about 0.5 l with a neutron flux of 2 MW/m^2 (9×10^{13} n/cm^2 s) and a total facility availability of 70%.

The required neutron flux is the same as that on the fusion reactor prototype (DEMO) first wall which give rise to a damage rate for iron of 20 dpa/fpy (displacements per atom/full power year). Neutron damage of materials originates primarily from collisions which displace atoms from the equilibrium position. This effect is quantified by the number of displacements suffered by an atom (dpa) due to neutron collisions.

The anticipated damage of the inner wall of DEMO at the end of its life is of the order of 150 dpa for iron.

Other requests concern some flexibility in choosing the maximum neutron energy and quasi-continuous operation. The former for a more effective use of the facility the latter because annealing times of defects shorter than the time between pulses and rate effects in the case of low duty-cycle source would introduce unacceptable uncertainties in the observed radiation effect.

This implies than flux perturbation caused by beam-off transients should also be minimized.

Finally the flux gradient in the irradiation volume should be less than 10% cm^{-1} in order to guarantee a uniform flux over the volume occupied by a material sample.

3 OVERALL FACILITY DESCRIPTION

Figure 1 shows the accelerators and test cells layout. Two parallel accelerators produce identical powerful beams of energetic deuterons with a suitable shaped cross section and energy spread.

The beams after a 90 degree bend are directed and overlap onto a liquid lithium jet target. A test assembly containing many samples of materials to be irradiated is sited very close to the lithium target. Lithium target and test assemblies are both housed in a well shielded test cell.

The two beams configuration minimizes flux perturbations caused by a beam-off transient in one of the accelerators as required.

Two lithium target and two test cell are provided to minimize time devoted to maintenance. Beams can be directed onto either one of the two targets. 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 two test assemblies could be irradiated simultaneously.

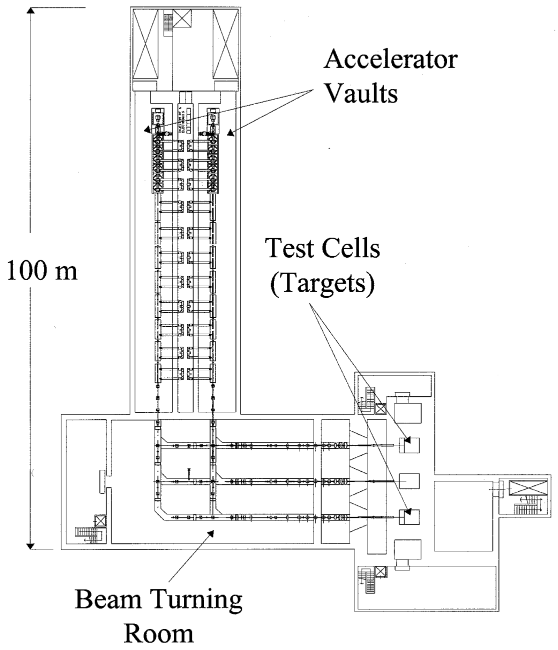


Figure 1: Accelerator and test cell layout

The accelerator systems along with the lithium loop (which feeds the targets) and test cells are located below ground level. Major power systems, hot cell facilities are located at ground level. The first floor level contains laboratories for the handling and testing of the irradiated components and specimens.

4 TEST FACILITIES

The neutron field produced by D-Li interaction spreads over a volume larger than the required 0.5 l, even though with a flux intensity decreasing moving away from the target. The extra volume available has been taken into account to test special materials employed in reactor regions far from reacting plasma submitted to a lower neutron flux.

According to the neutron flux range, four regions have been considered: a high flux (> 20 dpa/fpy), medium flux (20 -1 dpa/fpy) low flux (1 - 0.1 dpa/fpy) and a very low flux region (0.1 - 0.01 dpa/fpy). The first is devoted essentially to test reactor first wall materials, tipically ferritic and martensitic steel, vanadium alloys etc. Matrixes of many hundreds of miniaturized specimens can be accomodated in a Vertical Test Assembly (VTA1) which provides a safe connection between the irradiation zone and the adjacent service hot cells. Adequate specimens cooling or heating is provided by means of He or NaK.

Specimen irradiation temperatures ranging from 250 up to 1000 °C are in fact required for realistic tests. The second region, medium flux region, is devoted to “in situ” experiments which are set up on a second Vertical Test Assembly (VTA2). Some tests infact such as measurement of tritium released from blanket materials or measurement of radiation induced conductivity must be performed during neutron irradiation. The third and fourth regions, low and very low flux regions, are equipped with a Vertical Irradiation Tubes (VIT) system consisting of an array of tubes acting as a multiple rabbit system. Specimens of special materials such as material for superconducting magnets, organic insulators, radiofrequency windows contained in pneumatic capsules can be easily placed/removed in/from the irradiation region. Cooling systems using liquid or gaseous helium or liquid nitrogen provide the required low temperatures down to 4 K.

VTA1,VTA2 and VIT are housed in a well shielded test cell together with the lithium target and support instrumentation. Figure 2 shows an elevation view of a test cell section.

Immediately above the test cell region large hot cells allow a safe removal/installation of test assemblies from/into the test cell.

Any maintenance and assembling/disassembling activity in the test cell and hot cells is performed by means of remote controlled equipments.

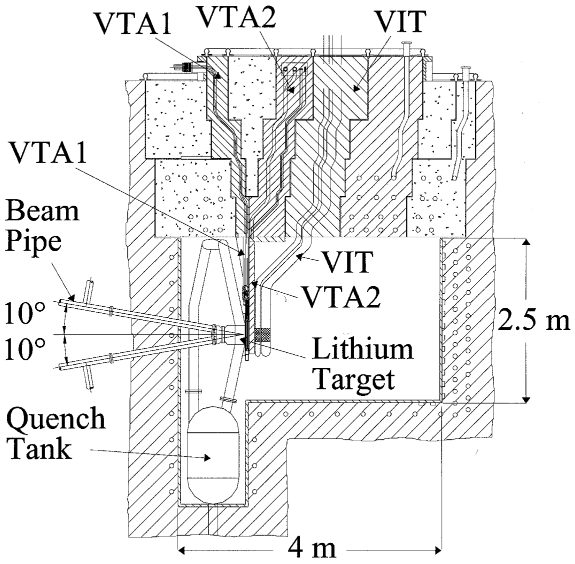


Figure 2: Elevation view of test cell section

Irradiated specimens are investigated for mechanical properties and microstructure in laboratories consisting of conventional testing instrumentation housed in hot cells or glove boxes sited close to the test cell region. Tritium exposure to personnel or environment in case of tritiated speciments is avoided by effective tritium retention systems.

5 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 to be presented to the deuteron beam the latter circulates the lithium and removes the heat deposited by the beam. 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, the modified FMIT-type target with a replaceable backwall has been selected for the baseline design.

The replaceable backwall is bolted to the back and sides of the target assembly. Seals around the edges will be needed 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 neutron damage for a potential 20-years lifetime. The replaceable backwall can be made of a material different from that of the target assembly if desired. For example a combination of ferritic steel target assembly and vanadium alloy backwall could increase the target system lifetime. The final backwall material choice will be determined by actual beam-on target testing during the initial 2-years of operation of IFMIF. Table I summarizes the lithium jet parameters.

Table I: Lithium jet parameters (40 MeV, 250 mA)

Jet thickness, m	0.025
Jet width, m	0.26
Jet velocity, m/s	15 (range 10-20)
Inlet temperature, °C	250
Outlet temperature, °C	300 (for 15 m/s)
Beam footprint, cm^2	5×20

6 ACCELERATOR SYSTEM

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 accelerator, shown in Fig. 3 (elevation view), comprises a sequence of acceleration and beam transport stages. The ion source generates a cw 140-mA deuteron beam at 100 keV. A Low Energy Beam Transport (LEBT) guides the deuteron beam from the operating source to a Radio Frequency Quadrupole (RFQ) Accelerator. The RFQ bunches the beam and accelerates125 mA to 8 MeV. The 8 MeV RFQ beam is injected directly into a Room-Temperature (RT), Drift-Tube-Linac (DTL) of the conventional Alvarez type with

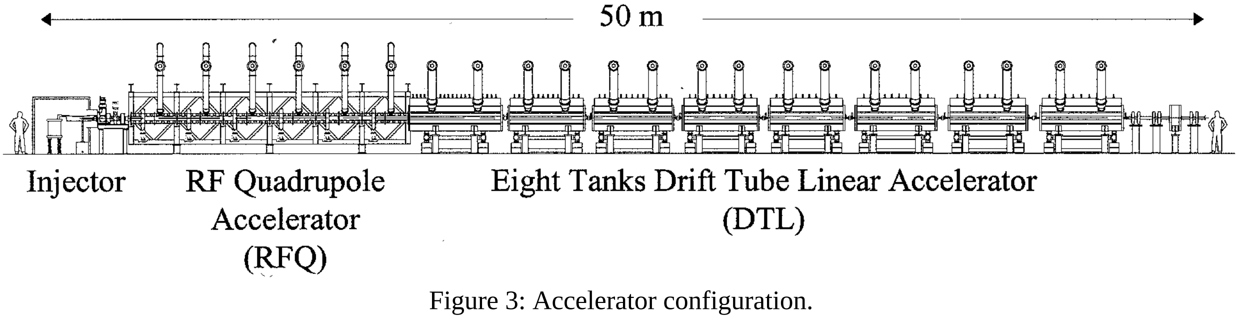


Figure 3: Accelerator configuration.

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. Beam loss in the accelerator is to be limited so that maintenance can be "hands-on", i.e., not requiring remote manipulators. However, the accelerator facility will be designed in such a way that remote maintenance is not precluded.

7 PROJECT EVALUATION

The two-year CDA for IFMIF was completed at the end of 1996.The Fusion Power Coordinating Committee (FPCC) of IEA expressed appreciation for the results obtained and recommended further technical studies to complete the database for an engineering design and to reduce technical risks. Hence, a Conceptual Design Evaluation (CDE) phase lasting for a two-year period (1997-98), supported by the same CDA team was launched.

The first task of the CDE phase carried out in 1997 was to identify critical items in the IFMIF conceptual design.

As far as the test facilities are concerned, the use of NaK, to control the specimen temperature, and the uncertainties in the evaluated neutron and gamma yields of the D-Li reaction were identified as items to be further investigated.

NaK has excellent heat transfer properties but at the same time is chemically reactive and becomes activated after irradiation, whereas He has relatively poor heat transfer properties but is chemically inert and has no activation concerns. A final decision, however, on the replacement of the NaK by the He-gas cannot be made before a high-flux helium-cooled test module has been designed in detail, fabricated and tested.

The uncertainty in the total neutron yield from D-Li reactions contributes directly to uncertainties in the engineering responses and, therefore, the available high-flux test volume. Owing to the importance of determining accurately the available irradiation volume, an improvement of the model is underway, including additional reaction components.

Critical issues for the accelerator are considered the availability of both very high power cw RF tubes and reliable codes to simulate the RFQ operation. A first step to solve the first issue has been the demonstration of the Thomson tube 1-MW 200-MHz cw diacrode operation for one hour (IFMIF specification for a feasibility demonstration was 1 MW for 100 hours).

Work is in progress on the second issue. Simple and fast codes are considered adequate for the IFMIF RFQ analysis but benchmarks have been suggested among those proposed.

Critical issues for the lithium target are considerd lithium-jet stability and the lifetime of the target backwall. Water experiments for a target model were successfully performed recently. A high-speed (<17 m/s) stable water jet with uniform velocity distribution was produced at the nozzle exit. The free surface of the jet was covered by acceptable low-amplitude two-dimensional and/or three-dimensional waves and their size did not change much over the tested jet length of about 130 mm. This result is very promising but further tests using a more realistic target model are needed.

The design adopted in the CDA has been based on a replaceable backwall which is bolted to the target assembly. This solution, however, requires the vertical test assemblies to be removed in order to allow backwall replacement. A new target design with a removable backwall which avoids the removal of the vertical test assemblies is considered highly desirable and will be developed in the CDE phase. The design will also consider the possibility of using a YAG laser to weld the backwall directly to the target body in order to improve the sealing capability of the removable backwall.

8 PROJECT COST AND SCHEDULE

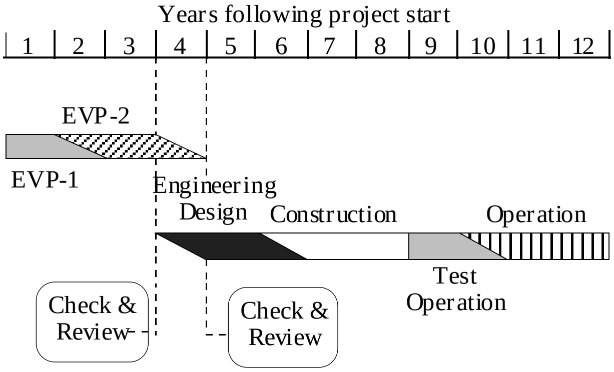
The IFMIF design team developed the overall cost estimate in a very open way so that each country is aware of the areas where national considerations are different. Many of the individual estimates were developed by specialists from two or more countries.

Rather than selecting an average cost within the range of the differences, the final estimate for the CDA was selected to be more representative of the cost for construction in Europe and the U.S. The estimate quoted internally by Japan is expected to be somewhat higher.

A summary of the baseline cost estimate is given in Table II.

Table II: Summary of IFMIF cost estimate

System	Estimated Costs M$ (US) - Jan 1996
Project management	52
Test facilities	107
Target facilities	115
Accelerator facilities	409
Conventional facilities	90
Central control system and common instrumentation	24
Total construction cost	**797**
Startup and commissioning	63
Engineering validation phase	49
Total project cost	**910**



EVP: Engineering Validation Phase

Figure 4: Top level IFMIF schedule developed during the CDA.

The total estimated construction cost of 797 M$ includes an allowance for indeterminates of 168 M$ which is distributed among the various systems.

The long range schedule for the IFMIF program which was developed for the CDA is shown in Fig. 4.

The Engineering Validation Phase (EVP) is assumed to start in Year 1 of the project, sometime after the completion of the CDA.

It includes the design, development and testing of prototype components necessary to prepare for engineering design and construction.

It also includes time for the checking, review and approval by the individual possible parties to the IFMIF program.

The decision taken by the IEA to postpone any decision on the next step of IFMIF design after the completion of the design evaluation phase (CDE) means that the year 1 of the schedule in any case follows 1998.

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