The IFMIF Test Cell – Design and Neutronics Overview


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Abstract. The International Fusion Materials Irradiation Facility, IFMIF, is an intense neutron source driven by two 40 MeV deuteron beams striking a joint lithium target producing neutrons with a peak around 14 MeV. The neutrons produced within a footprint of 20 cm width by 5 cm height are penetrating the high-flux (0.5 litres, 20-55 dpa/full power year), medium-flux (6 litres, 1-20 dpa/fpy), and low-flux (>100 litres, <1 dpa/fpy) test modules. Irradiation simulation calculations on the basis of recently developed nuclear data libraries and advanced neutronics computational tools have shown that IFMIF offers not only favorable conditions for structural materials in the high flux volume but can also be used as very suitable test bed for achieving DEMO-specific dpa, Helium and \(^3\)H production rates for the neutron multiplier Beryllium. The recently improved design of the high flux test module (i) increases the available high flux test volume by ~20%, (ii) reduces the flux gradients by ~10%, (iii) maximises the available space for specimens by ~30%, and (iv) allows individual rig temperatures with practically homogeneous temperature profiles during irradiation and beam-off periods.

1. Introduction

The qualification of materials under fusion-specific conditions for lifetimes of at least 10-15 MWy/m\(^2\) is inevitable for the design, construction, and safe operation of fusion power reactors and is a critical requirement on the path to fusion power. Therefore, the timely availability of the International Fusion Materials Irradiation Facility, IFMIF, has become a major element in fusion strategy scenarios. International preparations on technical and administrative levels are presently made to enter a 5 years EVEDA (Engineering Validation and Engineering Design Activity) phase that includes experimental verification of major subsystems as well as establishing all engineering data for licensing and construction. Based on the reference design [1, 2] and on various recent performance improvements [3, 4, 5, 6] an overview on the entire IFMIF is given with special emphasis on users’ attractiveness, neutronics and Test Cell design.

2. Test Cell and Test Modules

IFMIF is an intense neutron source driven by two 40 MeV deuteron CW linear accelerators with 125 mA beam current, each striking a joint flowing lithium target under a 20° impinging angle producing neutrons with a peak around 14 MeV. The neutrons produced within a footprint of 20 cm width by 5 cm height are mainly emitted in forward direction, where the high-flux (0.5 liters, 20-55 dpa/full power year), medium-flux (6 litres, 1-20 dpa/fpy), and low-flux (>100 litres, <1 dpa/fpy) test modules are located (Fig. 1 and with the enlarged test modules Fig. 2). The high-flux test module (HFTM) of the vertical test assembly 1 (VTA1) is devoted
to high-fluence irradiation of candidate structural materials in the high-flux volume (Fig. 1, red colour), the 2 medium-flux test modules (MFTM) of VTA2 are dedicated to more sophisticated in situ experiments like creep fatigue tests or Tritium release tests on breeder ceramics in the medium-flux region (magenta colour), while the vertical irradiation tube system (VIT) allows the irradiation of special purpose materials in the low-flux region (LFTM) (blue colour).

3. Small Scale Specimens

Rapid progress is made in the international materials community in developing a complete set of miniaturized samples of material intrinsic properties and proven scaling laws [7, 8].

<table>
<thead>
<tr>
<th>Specimen type and dimensions</th>
<th>Top Fatigue Bend/Charpy</th>
<th>Tensile Creep</th>
<th>Crack Growth</th>
<th>Fracture toughness</th>
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<td>Standard achieved</td>
<td>developed</td>
<td>International R&amp;D ongoing</td>
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Fig. 1: Test Cell with the deuteron beam from left striking the lithium target and the test modules

Fig. 2: Enlarged section of the target and the adjacent test modules on the right side.

Fig. 3: Small Scale Specimens
Significant volume reductions are achieved (20 – 125 times) compared to conventional standards. Reference geometries were reached already due to the today’s fission reactor irradiation program in case of the fatigue and tensile test specimens. Concerning Crack growth and fracture toughness specimen R&D is ongoing. The actual types and geometries are shown in Fig. 3. The length of the fatigue, tensile, Bend/Charpy and creep specimen was harmonized. For a complete overview on advanced materials for fusion technology see Ref. [9].

4. Neutronic calculations

The irradiation performance of both the high-flux and the medium-flux test modules has been significantly improved on the basis of recently developed nuclear data libraries and advanced neutron transport calculations.

The nuclear design of the test modules was based on neutronic calculations with the Monte Carlo code McDeLicious. This code was developed as enhancement to the standard MCNP Monte Carlo code with the ability to sample in the transport calculation the generation of d-Li source neutrons on the basis of tabulated d-Li cross-section data. [10,11]. The McDeLicious approach was extensively tested against available experimental thick lithium target neutron yield data showing that the D-Li neutron generation can be predicted with the currently best achievable accuracy [11].

As an application example, Fig. 4 shows a contour plot of the damage production rate (dpa/fpy, displacement rate per atom and full power year) in the HFTM calculated with McDeLicious for full power.

Fig. 4: Contour plot of the damage at three vertical levels (lower diagram: mid plane; middle diagram: 2.5 cm above mid-plane and upper diagram: 3.25 cm above midplane); the beam enters from below; the red lines correspond the geometrical boundaries of the HFTM reference design 20 x 5 x 5 cm$^3$
operation of the two IFMIF beams. A steel density of 80% (Eurofer steel) was assumed for the HFTM in these calculations. The HFTM was surrounded by a steel reflector with a thickness of 10 cm. The requirement for a 0.5 liter volume with a damage rate greater than 20 dpa/fpy is achieved by extending the specimen stack in the HTFM to 25 mm above the height of the beam foot print of 50mm. Recent irradiation simulation calculations for the MTFM have shown that IFMIF offers not only favourable conditions for structural materials in the high flux region but also can be used as very suitable test bed to achieve DEMO-specific dpa, Helium and $^3$H production rates for the neutron multiplier Beryllium [12].

For IFMIF activation and transmutation calculations, the Intermediate Energy Activation File IEAF-2001 has been recently developed [13]. IEAF-2001 contains neutron-induced activation cross sections for 679 target nuclides from Z=1 (hydrogen) to 84 (polonium) up to 150 MeV. Two working libraries in different data formats have been derived for application calculations [14]. One of them can be used by activation codes capable of handling an arbitrary number of reaction channels such as ALARA (Analytical and Laplacian Adaptive Radioactivity Analysis) of the University of Wisconsin-Madison. The other one was developed only recently for use with the FISPACT activation code of UKAEA Culham. It uses pseudo fission product yields to describe the generation of transmutation products under irradiation. Recent applications include the assessment of the elemental transmutation in the Eurofer specimens of the HFTM and the activation of Lithium and test cell components in IFMIF.

5. HFTM design

The specimens shown in Fig. 3 are piled up to a stack which is installed in capsules. The space between the specimens is filled with sodium or a potassium/sodium alloy in order to guarantee the heat transfer between the specimens and the specimens and the capsule walls (Fig. 5).

The capsule is surrounded by a triple heater system. The heaters are operated and controlled by three thermocouples per capsule individually. It allows keeping the specimen at beam-on and beam-off periods at temperatures with an allowance of ±15 °C over a stack height of 66 mm. Smaller temperature allowances could be achieved however at the price of additional heaters and less space for specimens. The temperature conditions of capsule volume beyond 66 mm are well known, so that the specimens can be used. As can be taken from Fig. 5, the stack width is less than 10mm. This follows from the temperature limit which is given by the
necessary temperature difference to conduct the nuclear heat through the stack to the capsule wall. The height reaches 81 mm. This dimension and the inner capsule width of 9.3 mm result from studies towards a maximum specimen density and arrangement flexibility in the capsules.

The capsules are installed in rigs. A gap filled with stagnant helium acts as thermal insulation between the rig and capsule walls. 12 rigs are positioned in a container subdivided in 4 compartments (Fig. 6). The outer dimensions of all rigs are the same so that they can be installed at each container position. The electric and nuclear heat is removed by helium which flows upward between the rigs.

![Fig. 6: HFTM container with four compartments separated by stiffening plates. Each compartment houses three capsules](image)

In this way, the design has been significantly improved during the past two years [15]. In combination with thermal hydraulics and fluid dynamics calculations, the neutron reflector made of reduced activation ferritic steel the following improvements were achieved: (i) the available high flux test volume has been increased by ~20%, (ii) the flux gradients has been reduced by ~10%, (iii) the available space for specimens was increased by ~30%, and (iv) the individual rig temperatures enable practically homogeneous temperature profiles during irradiation and beam-off periods. At the same time the 12 rigs have become larger, thus allowing a much higher flexibility in specimen test matrix arrangements. An alternative high flux test module design with horizontal rigs is also being developed [16].

6. Thermo-hydraulic layout of the helium cooled HFTM

The widths of the helium gaps between the rigs were chosen according to the design goal: maximum space for the specimens. Therefore, they are 1mm at the longer sides and 0.5 mm at the smaller sides (see Fig. 6). The helium pressure was stipulated to be at 0.3 MPa in order to keep the pressure load on the container wall low. As consequence, the helium velocity comes close to 0.5 Mach. Even though the Reynolds number is < 10000 and the flow regime is in the transition range laminar/turbulent. The channels are too short for a complete evolution of the flow pattern. The rectangular channels have flow fields deviating from those in tubes. The heat load at least at the hottest rigs may create relaminarization of the boundary layer which impairs the heat transfer.
The lay-out of the HFTM was done by means of CFD calculations with the code STAR-CD. The code offers several turbulence models. The code and the models were validated with the experimental data of Shehata and McEligot[17]. The experiments were conducted with air flowing upwards in circular tubes. Data calculated with the linear k-ε low Reynolds-model showed a good agreement with the experimental data. With this model the code iterates to a stable solution in a reasonable time. However, the conditions in the HFTM differ in several respects from these experiments. Therefore, a helium loop with appropriate experimental sections for code validation is taken in operation. Necessary adaptations of the code or the models will not question the design in principal as presented above. However, the subdivision and arrangement of the triple heater section can be determined only if the heat transfer along the channels is reliably predicted. On the other hand, the build-up of the test loop provides valuable information on the handling of helium and measurement devices (Fig. 7).

7. MFTM design

The medium flux test modules are being investigated in several design variants. A major result of several iteration steps between neutronics and design calculations is that the shape of the IFMIF neutron spectrum now follows, over several orders of magnitude, that of a DEMO reactor breeding blanket, (i) if a neutron spectral shifter made of tungsten is placed between the creep fatigue test module and the $^3$H release test module, and (ii) if all test modules are enwrapped with 25-35 cm of the neutron reflector material graphite. Altogether, the neutronics and design studies have confirmed the suitability and flexibility of the IFMIF reference design in principal.

The in situ creep fatigue test module allows the simultaneous irradiation and mechanical testing of three standard sized push-pull specimens located in the irradiation window of the beam footprint. In spite of the sophisticated test technology, these specimens are hollow to allow a defined inner cooling with helium gas operating at a low pressure of about 0.3 MPa. Detailed analysis aim at amendments of the temperature distributions in the creep fatigue specimens.
Simulation calculations performed with STAR-CD and based on the neutronic calculation as described above show that the specimen can be kept with ohmic heating and insulations against the adapters at temperatures with an allowance of less than 5% over almost 50% of the specimen length. This comprises the sensitive region for the tests.

8. Design integration

The design work has made significant progress during the last few years. Recent meetings of the IFMIF Test Cell designer groups revealed the need for design integration of the components within the test cell. Fig. 8 shows an integration of all available drawings of the test cell.

Fig. 8: Integration of all available drawings of the test cell for demonstrating the need for design integration

9. Conclusions

Significant progress has been achieved in the design of the IFMIF Test Cell. The dedicated Monte Carlo code McDeLicious was used for the neutronic design calculations of the test modules. McDeLicious has been validated on the basis of several experiments for thin and thick lithium targets. The thermo-hydraulic lay-out was based on calculations with the CFD code STAR-CD. The prediction of this code using different turbulence models were compared with experimental data available from literature. As the conditions in these experiments correspond only partially to those of the HFTM, appropriate experiments are under preparation. The HFTM design was improved during the last two years towards a 30% higher specimen package density, lower temperature allowance and a higher flexibility with respect to loading matrix.
References

[2] IFMIF Key Element Technology Phase Report; JAERI-Tech 2003-005 (May 2003); The International IFMIF Team
[6] H. Matsui et. al., The present Status and Prospects for the IFMIF Project, 23rd SOFT 2004