IFMIF
Necessity and Status of Preparation

Presented by Eberhard Diegele, F4E

International Workshop, MFE Road Mapping in the ITER Era
8th September 2011, Princeton

This contribution and any comments *during* the workshop
do not necessarily represent the opinion or the policy of the EC or F4E
Elements of a Strategy for Materials R&D – for the next Two Decades (I)

RAFM steels „only“ choice for TBM (alternative options with high risk)
- Development mission driven. Technology part of the programme
- Full characterisation of RAFM steels in the next decade (for TBM use).
- „Code qualification“ required up to some dpa [RCC-MRx/SDC].
- Irradiation campaigns in fission reactors („Material Test Reactors“).

Test materials with fission neutrons from nuclear reactors:
- Adequate flux.
- BUT
  - Energy spectrum: not adequate, high energy tail missing.
  - Insufficient H and He production by transmutation.
Elements of a Strategy for Materials R&D – for the next Two Decades  (II)

Construct and start operation of a 14 MeV neutron facility (IFMIF)
  • Adequate flux,
  • Fusion typical irradiation temperatures
  • At “homogeneous” test conditions throughout a sample.
  • Stable irradiation conditions (T) (#)

IFMIF
is „mandatory“ to generate engineering data for DEMO design rules for End of Life conditions.
is useful in testing materials and sub-components prior to approval for application in power plants. DEMO will provide the endurance component tests.
Is a most valuable source for verifications of multi-scale modelling predictions.

Code qualify material:
Property f (T, T_{irrad}, fluence, environment, load-stress-strain) – This allows to together with a code framework transferability to other conditions
With temperature excursions (annealing of defects) – risk to loose data point
Elements of a Strategy for Materials R&D – for the next Two Decades - (III)

The He issue

• Fission reactors produce insufficient rates of He and H
• Irradiation in fission reactors gives only non-conservative approach for degradation of materials.

Various tricks or methods used:
- B and Ni-doped steels in MTR: ~a few appm He/dpa.
- Fe\(^{54}\) enriched steels in MTR: ~2 appm He/dpa.
- Mixed spallation-neutron spectrum: ~100 appm He/dpa.
- (Multi) Ion beam irradiation: up to 10000 appmHe/dpa.

• All these experiments needed to increase knowledge and understanding of the microstructure.
• Modelling and understanding of irradiation results under various conditions is clearly needed.
Elements of a Strategy for Materials R&D – for the next Two Decades - (IV)

- Accompanying programs:
  - Modeling of irradiation effects towards an understanding of irradiation damage over the full scale (from quantum physics to engineering analyses).
  - “Extrapolation” of dislocation damage from fission data to fusion environment.
  - Simulations with predictive capability.
  - Integrated approach with “physics-based” modeling and simulations in the meso to macro scale at the interface between materials science and technical application (simulating “real conditions” and “real components”) will be an key for success.
Elements of a Strategy for Materials R&D – for the next Two Decades - (V)

- In parallel: Optimization and further development of RAFM steels
  - For use with DEMO
- In parallel: Optimization and further development of ODS/NCF-type steels
- In parallel: Development of „new“/“advanced“ materials for high temperature application.

Including, both

Irradiation campaigns in fission reactors (high fluence, ~100 dpa).

Strong science based programme to accumulate knowledge and understanding of irradiation effects to „design materials“.
Long Term Materials Development

The EU Road Map

E. Diegele
EDFA-CSU Garching

IEA-Meeting July 10-12, 2006, Tokyo, Japan
### Materials Performance/Component specific Loading - Stage- IV
- Demonstrate solution to concept-specific issues
- Performance under complex loading history (T, stress, multi-axial strain fields & gradients) & environmental conditions

### Qualified Material, Demonstration of Performance - Stage- III
- Complete database for final design & licensing
- Validate constitutive equations & models
- Demonstrate life time goals (He issue)

### Demonstration of Performance Limits - Stage- II
- Database for conceptual design
- Demonstrate proof-of-principle solutions, design methodology
- Evaluation-modification cycle to optimize performance

### Materials Screening & Materials “Design” - Stage- I
- Identify candidate alloy composition, compatibility, irradiation stability, proof of principle for fabrication and joining technologies
- Validation of models and tools (microstructure)
Fusion Materials Development Path

Facilities needed

Performance under component specific loading **Stage IV**

IFMIF and FNSF are complimentary in an INTERNATIONAL Road Map or approach

Qualified materials, full demonstration of performance **Stage III**

14 MeV neutrons or fusion specific n-spectra >>> **IFMIF**

To some limited extend **ITER-TBM**

Demonstration of performance limits **Stage II**

Fission reactors (MTR of next generation like Jules-Horowitz) **(IFMIF)**

Materials “Design” R&D **Stage I**

Fission reactors (MTR)

Multi-ion-beam irradiation facilities

Complementary Modelling essential
Strategy on the address fusion neutron irradiation effects

Experimental understanding
- Dislocation damage, He effects, H effects, etc.
- Neutron irradiation (fission)
  - SSTT
  - Mechanical property data
    - Tensile
      - Hardness (Hv)
    - Toughness
    - Creep
    - Fatigue
    - (Misc)
- Ion beam irradiation
  - Nano hardness (Hm)
  - Mechanical property data
    - TEM
    - SEM
    - Residue
    - Others

Mechanical understanding
- Theory of Irradiation effect
  - Mechanical property model
  - Microstructure evolution model
  - Structure deformation model
- Theoretical prediction
- Computational Simulation
  - Irradiation fields correlation (dpa/s, PKA)
  - Point defect migration, agglomeration
  - Microstructure evolution
  - Etc.

Evaluation of fusion neutron irradiation effects on mechanical property

IFMIF irradiation

H. Tanigawa, Vienna Dec 2011, IAEA, modified
FNSF/DEMO Nuclear Facility Needs

- **Fission Reactors**
  - The capability to perform irradiation experiments in fission reactors is essential for identifying the most promising materials and specimen geometries for irradiation in an intense neutron source.

- **Fusion Relevant Neutron Sources**
  - Overcoming radiation damage degradation is the rate-controlling step in fusion materials development.
  - Evaluation of radiation effects requires simultaneous displacement damage (~150 dpa) and He generation (~1500 appm).

- **Fusion Nuclear Science Facility (predecessor to DEMO)**
  - Nuclear facility to explore the potential for synergistic effects in a fully integrated fusion neutron environment. Data and models generated from non-nuclear structural test facilities, fission reactor studies and the intense neutron source will be needed to design this facility.
**Early History**

**Need for a Neutron Source to Test & Qualify Materials for DEMO Recognized for > 30 y**

- U.S. Pathways Study [M.A. Abdou et al., Fus. Tech. 8 (1985) 2595-2645]
  - Concluded that fission reactors & accelerators “are useful and their use should be maximized worldwide, but that they have serious limitations”
  - Reactor use & new non-neutron facilities recommended “over next 15 years”
  - Low total power, high power density D-T devices then required for integrated tests & validation
  - Evaluated plasma sources (RFPs, high-density Z pinches, beam-plasma mirrors) and accelerator-based sources (d-Li, spallation)
  - Recommended further investigation of 3 options: d-Li, spallation, beam-plasma
- Subsequent analysis [D.G. Doran et al., J. Nucl. Mat. 174 (1990) 125-134]
  - Concluded that differences in damage parameters not great enough to permit a selection of preferred alternative on basis of displacement rate, primary recoil spectrum, & important gaseous and solid transmutations
  - Concluded that D-Li neutron source concept (basis of IFMIF) was preferred because of relatively lower neutron energy tail & most mature technology base
    - Beam plasma source found to provide best simulation of a fusion reactor, but scientific feasibility was still in question
    - Spallation source found not generally favored by materials community - would be “a viable candidate only if it can be attained at much less expense than the alternatives.”

Recent U.S. History

Similar Need for a Fusion Irradiation Facility
Recently Articulated by the U.S. Community

- 2007 FESAC (Greenwald) report
  - Selected fusion irradiation facility as one of nine unprioritized initiatives
  - Recognized such a facility is the IFMIF mission
  - Recommended assessing potential for alternative facilities to reduce or possibly eliminate the need for the US to participate as a full partner in IFMIF

- 2009 FES Research Needs Workshop (ReNeW)
  - Advocated a fusion-relevant neutron source to be an essential mission requirement
  - Cited 3 options (same as 1989 IEA) as examples for further evaluation and selected based on technically attractiveness and cost effectiveness

- 2011 FES Fusion Nuclear Science Pathways Assessment
Indicate that slides was provided by this group of authors

IFMIF in the Context of Materials Research


Authors on behalf of the fusion materials and IFMIF community
Perspectives for fusion

- Conception
- Construction
- Exploitation

Application of results

- ITER (1/2 GW_th)
- Accompanying Programme in Physics and in Technology
- Materials, Intense n-source
- Environment and Safety

- DEMO (2-3 GW_th)

- FPP (1.5 GW_e)

Large scale production of electricity

0 10 20 30 40 50 Years
High Performance Materials for Energy

First Reactors
1-3 dpa

Current Reactors
< 200 dpa

Advanced Reactors
< 200 dpa

Future Systems

Strategic Missions:
• Electricity, Hydrogen, Heat
• Contribute to lower greenhouse gas emission

Specific challenges for fusion:
• Short development path
• More demanding loading conditions

1-3 dpa
ITER IFMIF

DEMO, Fusion Reactor
< 150 dpa
20-40/year
Main missions of an intense neutron source in roadmaps to fusion power

- **Qualification of candidate materials**, in terms of generation of *engineering data* for *design*, *licensing* and *safe operation* of a fusion DEMO reactor, up to about full lifetime of anticipated use of DEMO.

- **Completion, calibration and validation of databases** (today mainly generated from fission reactors and particle accelerators).

- **Advanced material irradiation** (towards power plant application)
  - Promote, verify or confirm selection processes.

- **Validation of fundamental understanding** of radiation response of materials hand in hand with *computational material science*.
  - Science-related modeling of irradiation effects should be validated and benchmarked at length-scale and time-scale relevant for engineering application.
  - Experiments performed in IFMIF would validate assumptions or adjust parameters.
TOP Level Requirements for an Intense Neutron Source

- **Neutron spectrum**
  Should simulate the first wall neutron spectrum of a fusion reactor as closely as possible in terms of PKA spectrum, important transmutation reactions, and gas production (He, H)

- **Neutron fluence accumulation**
  Up to 120 dpa\textsubscript{NRT} in <4 years applicable to 0.5 litre volume.

- **Neutron flux and temperature gradients**
  Flux gradient <10% over the gauge volume of the Small Scale Specimens
  Temperature gradient ±3% within individual capsules (~90 specimens).

- **Machine availability**
  ≥ 70%

- **Time structure**
  quasi continuous operation

- **Good accessibility of irradiation volume & high flexibility for further upgrades**

High ranking International Advisory Panels (late 80-ies to mid 90-ies) concluded that these requirements can be best fulfilled with a D-Li stripping source.

IFMIF was born
TOP Level Requirements for an Intense Neutron Source

- **Neutron spectrum**
  Should simulate the first wall neutron spectrum of a fusion reactor as closely as possible in terms of PKA spectrum, important transmutation reactions, and gas production (He, H)

- **Neutron fluence accumulation**
  Up to 120 dpa\textsubscript{NRT} in <4 years applicable to 0.5 litre volume.

- **Neutron flux and temperature gradients**
  Flux gradient <10% over the gauge volume of the Small Scale Specimens
  Temperature gradient ±3% within individual capsules (~90 specimens).

- **Machine availability**  \geq 70%

- **Time structure**  quasi continuous operation

- **Good accessibility of irradiation volume & high flexibility for further upgrades**

High ranking International Advisory Panels (late 80-ies to mid 90-ies) concluded that these requirements can be best fulfilled with a D-Li stripping source.

IFMIF was born
**Fusion Power Plants: Material Challenges beyond ITER**

### Blanket: ≤30 dpa/yr, 2.5MW/m²

- **Reduced Activation Structural Materials:**
  - RAFM Steels (EUROFER) 300-550 °C
  - EUROFER-ODS 350-650 °C
  - SiC\(_f\)/SiC for sophisticated concepts

- **Functional materials**
  - neutron multipliers, breeder ceramics

- **Special purpose materials** (diagnostic,…)

### Divertor: ≤10 dpa/yr, 10-15 MW/m²

- **Refractory alloys (e.g. W-ODS)**
  - 850-1200 °C → 600 - 1300 °C

- **Nano-scaled RAF-ODS Steels**
  - 350-650 °C → 250 - 800 °C

**DEMONstration Reactor Concept**

- **Power:** 1.30 MW\(_e\)
- **Plant Efficiency:** 37-45%
Main Relations between ITER, IFMIF and DEMO

ITER

Deuterium-Tritium Test Blanket Modules

Design Const. Operation

~30 dpa ~70-100 dpa

Fission Reactor and Charged Particle Irradiation

IFMIF

Const Operation Operation

~10 years

DEMO
Is today IFMIF still the best choice?

Neutronics: IFMIF vs. the Spallation source MaRIE (1/8)

- Matter Radiation Interactions in Extremes -

The Materials Test Station (MTS) is a spallation source facility whose prime mission is the irradiation of fuels and materials in a fast neutron spectrum.
Neutron spectra

Relevant for damage and transmutations in steels

![Graph showing neutron spectra with different sample types and neutron energies.](image)
IFMIF vs. the Spallation source MaRIE (3/8)
Displacement Damage for different rigs

MaRIE 1 MW

Displacement [dpa fpy]

- Neutron
- Proton

Irradiation Rig #

5 dpa/y
IFMIF vs. the Spallation source MaRIE (4/8)

Displacement Damage: Comparison of facilities

- IFMIF BP: High damage with acceleration capability
- IFMIF HFTM: Moderate damage with no acceleration capability
- DEMO FW: Lower damage with no possibility for accelerated irradiation
- MTS #3 and MTS #7: Low damage with no possibility for accelerated irradiation

The graph shows the comparison of damage in different facilities, with IFMIF BP having the highest damage and accelerated irradiation capability, followed by IFMIF HFTM with moderate damage but no acceleration, and DEMO FW with lower damage but no possibility for accelerated irradiation.
IFMIF vs. the Spallation source MaRIE (5/8)

Helium Production

MaRIE, 1 MW

DEMO relevant He/dpa ratio in steels.

IFMIF meets the relevant ratio in all test modules.
Flux/volume considerations

MTS beam power = 1.8 MeV

IFMIF High flux

Volume for 20 dpa/fpy
IFMIF: ~ 500 cm³
MTS: ~ 250 cm³

Volume for 30 dpa/fpy
IFMIF: ~ 360 cm³
MTS: ~ 40 cm³

E. Pitcher, LANL

IFMIF vs. the Spallation source MaRIE (6/8)
IFMIF vs. the Spallation source MaRIE (7/8)

Spallation product accumulation

Eurofer composition irradiated up to 25 dpa (NRT)

- MaRIE sample can #3 (n + p)
- MaRIE sample can #7 (n + p)
- HCLL Demo (FW)
- HFTM

RAFM specification on S + P
<< 100 appm!
Segregation at grain boundaries
And promotes fracture
Effect of spallation elements on Ductile Brittle Transition

Drop of upper shelf energy:

- +0.25% Ti
- +0.96% C
- +0.04% S
- - 0.5% Mn
- +0.02% P

Elements like S, P enhance severely the brittleness of Cr-steels
Principle of IFMIF

**Accelerator**

- Source $140 \, mA \, D^+$
- LEBT
- RFQ $100 \, keV$
- MEBT
- Half Wave Resonator
- Superconducting Linac $5 \, MeV, 9, 14.5, 26$
- HEBT $40 \, MeV$

**Lithium Target**

- $25^{\pm 1} \, mm \, thick, \, 15 \, m/s$

**Test Cell**

- High (>20 dpa/y, 0.5 L)
- Medium (>1 dpa/y, 6 L)
- Low (<1 dpa/y, > 8 L)

**Beam shape:** $200 \times 50 \, mm^2$

**Typical reactions**

$^7\text{Li}(d,2n)^7\text{Be}$

$^6\text{Li}(d,n)^7\text{Be}$

$^6\text{Li}(n,T)^4\text{He}$
IFMIF: The Accelerator of all records!

Unprecedented challenges
- highest intensity
- highest space charge
- highest power
- longest RFQ
- Very high availability & reliability

True “Laboratory” for studying physics of High Intensity Beams (halo formation, core – halo interaction, emittance growth, sudden particle loss)
Current activities: EVEDA

- The Engineering Validation and Engineering Design Activities, conducted in the framework of the Broader Approach aim at:
  - Providing the **Engineering Design of IFMIF**
  - **Validating the key technologies**, more particularly
    - The low energy part of the accelerator (very high intensity, D+ CW beam)
    - The lithium facility (flow, purity, diagnostics)
    - The high flux modules (temperature regulation, resistance to irradiation)

- Strong priority has been put on **Validation Activities**, through
  - The **Accelerator Prototype** (Constructed in EU, tested in Rokkasho, JA)
  - The **EVEDA Lithium Test Loop** (to be tested in Oarai, Japan)
  - Two complementary (temperature range) designs of High Flux Test Modules and an in-situ Creep fatigue Test Module
IFMIF: Implementation and Actors of the Project

IFMIF/EVEDA Integrated Project Team

<table>
<thead>
<tr>
<th>Project Leader</th>
<th>Project Leader</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU Coordinator + FG Leaders</td>
<td>JA Coordinator + FG Leaders</td>
</tr>
</tbody>
</table>

Project Team
In Rokkasho

International Fusion Materials Community (Users)
Engineering Validation Activities

The Accelerator Prototype
Whole Accelerator with Beam Dump
All buildings were completed in March 2010.
Manufacturing of the injector

Blockhouse at Saclay

Ion Source

Solenoid
magnetic measurement

120 kV
250 mA

High Voltage Power Supply
Assembly of the EVEDA Lithium Test Loop

Facility Building
[40mW, 80mL, 33mH]
JAEA Oarai

- Commissioning undergoing
- Start of the experiments: June 2011

ELiTe Loop construction completed in November 2010
Engineering Validation Activities

The High Flux Test Module
High Flux Test Module current design

3,4,5,6: Irradiation Rigs
1,2,7,8: Companion Rigs

About 1000 samples
HELOKA-LP
Full scale helium gas coolant loop

Test section area

Compressor station
Advantages

- On time for DEMO design
- Possible some impact on ITER TBM operation
- Present IFMIF team and expertise is maintained along the time

Challenge

- Significant EU budget required during FP8 2014-2020
**Advantages**

- IFMIF close to the time for DEMO (first data of IFMIF at same time than ITER DT results)
- *Relatively low EU budget required before 2020* (the Host country can offer to support the International Team during some time)
- Expertise and team developed during EVEDA can be maintained
### IFMIF schedule - Pesimistic scenario

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Year 2010</th>
<th>Year 2015</th>
<th>Year 2020</th>
<th>Year 2025</th>
<th>Year 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EVEDA phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineering activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validation activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>IFMIF International Review</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decision to built IFMIF (that includes to built up the international consortium and the site decision)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>IFMIF CODA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start-up of international team</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed engineering (site adaptation, validation activities results,...)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IFMIF construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IFMIF commissioning and startup</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First data obtained</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Advantages
- No EU budget required before 2020

### Problems
- **IFMIF in the critical path of DEMO**
- The expertise developed during the EVEDA phase will be lost
**Scenario 1**

DEMO design (in-vessel) finished

**IFMIF**
- Prepare CODA
- Negotiations
- Complete design
  5-6 calendar years

Construction and commissioning
  6 calendar years

Irradiation+PIE
  *20-55 dpa/fpy
  70% duty cycle
  4 calendar years

*Irradiation+PIE*
  5-10 dpa/fpy, 30% duty cycle
  >15 calendar years!

*Materials data base:
~50 dpa for blanket
~20 dpa for divertor*
Summary and Conclusions

- IFMIF meets fully the mission and the requirements of an intense fusion neutron source and is able to deliver timely the major pillars of a materials database for construction, licensing and safe operation of a DEMO reactor.

- Main Milestones:
  - June 2015: Start of the experiments of the whole Accelerator Prototype
  - June 2017: End of the studies in the framework of the BA agreement
  - Dec. 2013: End of IFMIF EVEDA for all activities not contributing to the Accelerator Prototype

- It is expected that the Intermediate IFMIF Engineering Design Report will be the basis for an evaluation through for an international review panel. Based on that results, siting negotiations could start immediately.

- IFMIF needs funding during 2014-2020. Otherwise,
  - IFMIF will be at the critical path for DEMO, and
  - the power of the present team and its competence will be lost.