IFMIF, THE EUROPEAN-JAPANESE EFFORTS UNDER THE BROADER APPROACH AGREEMENT TOWARDS A Li(d,xn) NEUTRON SOURCE: CURRENT STATUS AND FUTURE OPTIONS

Article 1.1 of Annex A of the BA Agreement mandates IFMIF/EVEDA to produce an integrated engineering design of IFMIF and the data necessary for future decisions on the construction, operation, exploitation and decommissioning of IFMIF, and to validate continuous and stable operation of each IFMIF subsystem.

Signed in February 2007
Entered into force on June 2007
The Broader Approach Agreement
The plans for a Li(d,xn) fusion relevant neutron source for materials research are 40 years old.


P. Grand et al., *An intense Li(d,n) neutron radiation test facility for controlled thermonuclear reactor materials testing*, Nuclear Technology, Vol 29, 1976, p. 327

A worldwide R&D and design work has continuously been in place since the ‘70s

FMIT (80s) – ESNIT (90s) – IFMIF for last 20 years

Why these efforts? Are we technologically ready?
The accumulation of gas in the materials lattice is intimately related with the neutron energy

\[ ^{56}\text{Fe}(n,\alpha)^{53}\text{Cr} \]

(incident n threshold at \(~3\text{ MeV})

and

\[ ^{56}\text{Fe}(n, p)^{56}\text{Mn} \]

(incident n threshold at \(~1\text{ MeV})

Noble gases are not solved in metals

Swelling and embrittlement of materials takes place
Existing neutron sources do not provide the needed answers

Fission reactors have an average energy <2 MeV

Spallation sources present a wide spectrum with tails in the order of hundreds of MeV and are pulsed

No efficient $p^+$ or $\alpha$-particle generation
Unique features of fusion materials

Combination of

Displacement damage (>20 dpa/fpy)

He (~11 appm/dpa) & H (~45 appm/dpa) generation

Cyclic stresses ($\Delta \sigma \sim 10^2$ MPa)

Thermal loads (~ 10 MW/m$^2$)

Lead to undetermined changes of materials’ microstructure and properties
Do we need Fusion relevant n source?

Understanding the degradation of physical properties of the materials exposed to 14.1 MeV neutron flux is a key parameter for fusion reactors reliable design and facility licensing.

Experimental data is needed given the number of variables playing a primary role:
- neutrons spectrum
- neutrons fluence
- material temperature
- thermo-mechanical history and microstructure
- mechanical loading
- lattice kinetics...

In ITER ~3 dpa at its end of life
In a Fusion Power plant ~30 dpa/year
IFMIF is tailor-designed to provide adequate flux and suitable energy within sufficient volumes to cope with the needs of the fusion community.
IFMIF has successfully passed through all key steps of a major facility:

- **Conceptual Design Activity (CDA)** phase in 1996 as a joint effort of EU, Japan, RF, US
- **Conceptual Design Evaluation (CDE)** report in 1998 towards a design simplification and cost reduction
- The **Conceptual Design Report (CDR)** in 2004 co-written by a committee of EU, Japan, RF, US
- **EVEDA** phase since 2007 as a joint effort of EU (6 countries) and Japan as an efficient risk mitigation exercise to face the construction on cost and schedule
A flux of neutrons of \( \sim 10^{18} \text{ m}^{-2}\text{s}^{-1} \) is generated in the forward direction with a broad peak at 14 MeV and irradiate three regions:

- \( >20 \text{ dpa/y} \) in 0.5 liters
- \( >1 \text{ dpa/y} \) in 6 liters
- \( <1 \text{ dpa/y} \) in 8 liters

Materials will be tested in the PIE

**Availability of facility >70%**
IFMIF/EVEDA mandates

**Engineering Design Activities – EDA phase**

**Validation Activities – EVA phase**

**D\(^+\) Accelerator**
- Incident current 2 \(\times\) 125 mA CW
- Ion source
- LEBT
- RFQ
- MEBT
- Superconducting cavities
- HEBT
- RF Power
- 100 keV: 140 mA CW
- 5 MeV: 9
- 14.5 MeV: 26
- 40 MeV: 40

**Lithium Target**
- Thickness 25 ±1 mm
- Flow speed 15 m/s
- Test Cell
- High Flux Test Module
- 12 capsules (>1000 specimens)
- 250 °C < \(T_{\text{CAP}}\) < 550 °C
- +/-3% Δ\(T\) per capsule
IIEDR

IFMIF Intermediate Engineering Design report has been successfully accomplished. It was supported by former phases and an existing strong momentum and enthusiastic community. It includes:

- >100 high quality reports carefully edited and revised
- Interfaces with thorough 3D models, licensing scenarios, RAMI analysis, nuclear safety studies, beam dynamics,
- 35 Detail Design Description documents of all sub-systems and cost and schedule.
Engineering Design Activities (EDA) Phase

IFMIF

THE INTERNATIONAL FUSION MATERIAL IRRADIATION FACILITY

INTERMEDIATE ENGINEERING DESIGN REPORT

The IFMIF/EVEDA Integrated Project Team

Figure 3. List of documents of the IDEDR.
The Design of IFMIF is broken down in 5 facilities:

- **Accelerator Facility**
- **Lithium Target Facility**
- **Test Facility**
- **Post-irradiation and Examination Facility**
- **Conventional Facilities**

Facilities Design Description

Beam density distribution at the lithium target

Isometric View of the Lithium Target Facility

3D bird-eye view of the PIE Facility

Target and Test Modules arrangement in the Test Cell

Engineering Design Activities (EDA) Phase

3D Cutaway view of the Test Facility – Main Room are represented

3D View of the main components of the IFMIF Accelerator

J. Knaster et al.

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Aachen
The status at the moment of the release of the IIEDR was described in an extensive paper in Nuclear Fusion.

J. Knaster et al., *IFMIF: overview of the validation activities*, Nuclear Fusion 53 (2013) 116001

things have evolved substantially since 2013

Technical challenges have been overcome
Possibly 5 major historical technical concerns

1st concern: D⁺ accelerator of 125 mA CW at 40 MeV
D⁺ prototype accelerator of 125 mA CW at 9 MeV in Rokkasho

2nd concern: Stable flow of lithium at required performance
Lithium loop with same operational conditions in Oarai

3rd concern: Irradiated capsules allowing independent cooling
A prototype High Flux Test Module in KIT

4th concern: Small Specimens Test Techniques
Shape validation for pending specimens in Japan

5th concern: 2 x 5 MW beam vs target interaction
Suitable concave backplate design & lithium conditions prevent boiling
Features of IFMIF vs LIPAc
d\(^+\) accelerator

125 mA CW
5 MW vs 1.125 MW
Space charge issues
Low energy/high power

So are LIPAc as IFMIF
within present accelerator technology

NGHIEM, P.H.P. et al., The IFMIF-EVEDA
Challenges in Beam Dynamics and their Treatment, Nucl. Inst. Meth. 654 (2011) 63–71

WEI, J. et al., The very high intensity future, IPAC 2014, Dresden
Breakdown of contribution for LIPAc

Equipment designed and constructed in Europe
Installed and commissioned in Rokkasho

- Injector + LEBT
  CEA Saclay
- RFQ
  INFN Legnaro
  JAEA
- MEBT
  CIEMAT Madrid
- SRF Linac
  CEA Saclay
  CIEMAT Madrid
- HEBT
  CIEMAT Madrid
- BD
  CIEMAT Madrid
- Diagnostics
  CEA Saclay
  CIEMAT Madrid
- Cryoplant
  CEA Saclay
- RF Power
  CIEMAT Madrid
- Building
  JAEA

CEA Saclay
CIEMAT Madrid
SCK Mol

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Space charge issues play a relevant role at high currents being severe at low-$\beta$; they cancel in relativistic regions.

Space charge induced emittance growth limits high currents.

The *perveance* figure of merit for space charge issues is world highest in LIPAc.

$$K = \frac{el}{2\pi\varepsilon_0 m_0 v^3 \gamma^3}$$

Deuterons present high inelastic cross sections; commissioning would be difficult if done with deuterons but protons at half energy and half intensity behave as deuterons at nominal conditions.

F. Scantamburlo *et al*., LIPAc, the 125 mA/9 MeV CW deuteron IFMIF’s prototype accelerator: what lessons have we learnt from LEDA?, IPAC 2014
The 1st attempt to run a RFQ in CW was in Los Alamos (LANL) for FMIT accelerator validation exercise. The ‘beam halo’ was discovered the rough way. Beam quality injected in RFQ was poor.

In 90s ECR approach was technologically validated for H⁺ in Chalk River.

LANL successfully operated LEDA in 2000. 100 mA in CW at 6.7 MeV with a dual electrodes capacitive/inductive part cooling RFQ tuning and unraveled beam halo physics the following years.

Alvarez type accelerating structure (DTL) for beam energies within 0.2<\beta<0.6 is a difficult challenge in CW. The feasibility of superconducting resonators for low-\beta was demonstrated in LANL in 2002.

LIPAc implements best possible technologies.
Phase A: 140 mA deuteron current at 100 keV in CW

Phase B: 125 mA deuteron current at 5 MeV at 0.1% duty cycle

Phase C: 9 MeV deuteron current at 9 MeV at 0.1% duty cycle

Phase D: Ramp up the duty cycle up to CW
D^+ (95% species fraction)

Ion Source ECR (2.45 GHz) - CW

E = 100 keV
I = 140 mA

emittance of $0.25 \pi \text{ mm\cdot mrad}$

Availability > 95%

Beam in Rokkasho >100 mA at 100 keV

an impossible performance for cathode based ion sources

R. Gobin et al., Final Design of the IFMIF Injector at CEA/Saclay, IPAC 2013, Shanghai

1st concern: D+ accelerator of 125 mA CW at 40 MeV

Emittance at Two Positions w/wo Solenoids

No Solenoids Current
Middle of Two Solenoids
After the Cone

100keV Deuterium
I_{ext} = 111 mA
RF = 500 W

D+: D_{2+}, D_{3+} = 87:13
D_{2+}
D_{3+}
D+

ε = 0.171 π.mm.mrad
ε = 0.193 π.mm.mrad
ε = 0.229 π.mm.mrad

13 October, 2015
Commissioning of IFMIF Prototype Injector

Accomplishment of Phase A possibly in 2015
The beam emittance at the RFQ input is crucial for an efficient beam transport along the RFQ.

A. Pisent et al., IFMIF-EVEDA RFQ design, EPAC2008, Genoa

M. Comunian et al., Beam dynamics redeisgn of IFMIF-EVEDA RFQ for a larger input beam acceptance, IPAC2011, San Sebastián

1st concern: D+ accelerator of 125 mA CW at 40 MeV

175 MHz; $I_{\text{output}} = 125$ mA CW; $E_{\text{output}} = 5$ MeV

625 kW beam average power

Max surface field 25.2 MV/m (1.8 Kp)

9.7 m long, the longest RFQ in the world

A. Pepato et al., Engineering design and first prototypes tests of the IFMIF-EVEDA RFQ, IPAC2010, Kyoto

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A Technological Wonder
Stainless steel & Cu brazed structures
Machining precision of electrodes within few tens of μm
Alignment along 10 m within few hundreds of μm

1st concern: D+ accelerator of 125 mA CW at 40 MeV

A. Grenspan et al., The IFMIF real scale aluminium model: RF measurement and tuning, *IPAC2010, Kyoto*

A. Palmieri et al., Perturbation analysis on a 4-vane RFQ, *IPAC2010, Kyoto*
1st concern: D+ accelerator of 125 mA CW at 40 MeV

Getting ready for the ensuing commissioning phases
The liquid Li screen beam target presents two functions:

- react with the deuterons
- to generate a stable neutron flux in the forward direction

- dissipate the 10 MW beam power

To efficiently fulfil both functions, it shall present a stable flow to the deuteron beam to completely absorb the 10 MW average power and protect the thin RAFM backwall that channels it.
The mandate was challenging
The demonstration
of the flow operational conditions of IFMIF lithium target
Lithium temperature at 250 °C
Flow speed at 15 m/s
Stable flow with +/- 1 mm amplitude
$10^{-3}$ Pa on free surface
Long term operation stability
Free surface interferometry diagnostics
Feasibility of Impurities in lithium <10 ppm
World largest liquid Li loop constructed by MHI and JAEA in Oarai

Started operation in March 2011
Severely damaged by Great East Japan Earthquake
Restarted August 2012
Accomplished its mission on Oct 2014

H. Nakamura et al., Latest design of liquid lithium target in IFMIF, Fusion Engineering and Design 83 (2008) 1007–1014

H. Kondo et al., Completion of IFMIF/EVEDA lithium test loop construction, Fusion Engineering and Design 87 (2012) 418
2nd concern: Stable flow of lithium at required performance

The result of 25 days continuous operation (24 h/day)

Long term flow stability within needed thickness fluctuations demonstrated

E. Wakai et al., Po 3-62
ENGINEERING VALIDATION FOR LITHIUM TARGET FACILITY OF THE IFMIF IN IFMIF/EVEDA PROJECT
Corrosion/erosion of non-stagnant lithium on-going

Flowing Lithium at $15 \text{ m/s}$ at $330 \, ^\circ \text{C}$
N content as specified for IFMIF
will test corrosion of 8 specimens
of EUROFER and F82H RAFM

Test time planned:
Short (1000 h)
Middle (2000 - 3000 h)
Long (4000 - 6000 h)
### HFTM functions and requirements

- To irradiate qualified SSTT specimens of RAFM steels in sufficient quantity/pace for IFMIF mission
- Irradiation temperatures in the range $250^\circ \text{C} \leq T_{\text{irr}} \leq 550^\circ \text{C}$ (for RAFM steels)
- Maintain low temperature spread ($\pm 3\%$ of $T_{\text{irr}}$ in 80% of specimen stack and temporal stability)
- Design for component lifetime of 1 year, 50dpa, meet RAMI requirements
- Integrate with IFMIF plant requirements (remote handling, (dis)assembly in hot cells, safety, waste disposal)

**3th concern:** Irradiated capsules allowing independent cooling

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**Stolen from Frederik’s invited talk tomorrow (at 08.30)**

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**F. Arbeiter et al., I61**

**Design Description and Validation Results for the IFMIF High Flux Test Module as Outcome of the EVEDA Phase**

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**Aachen**
Combined effect of capsule heaters, clever cooling channels design, NaK filling thermalization and He gas cooling showed the target temperature uniformity (17 thermocouples per capsule)

Target T uniformity of specimens demonstrated
Small specimens are neither exclusive of fusion nor a new technology.

Under EVEDA intense work has been developed on

**Fatigue**

**Fracture toughness**

**Crack growth rate**
4th concern: Small Specimens Test Techniques

12 capsules within beam footprint
x2 sets of 40-45 spec/capsule
within 3% ΔT/capsule

Thermalized with NaK

8 compartment
4 central directly irradiated

Fatigue A

Fatigue B

Bundle-2 Bundle-1
Alloy B Alloy A

80-90 specimens/capsule

Specimen filling in hot cell

Fatigue A

Fatigue B

Bundle-2 Bundle-1
Alloy B Alloy A

Thermalized with NaK

8 compartment
4 central directly irradiated

Fatigue A

Fatigue B

Bundle-2 Bundle-1
Alloy B Alloy A

80-90 specimens/capsule

Specimen filling in hot cell
Fatigue seems to work nicely

An adaptation is being studied

Efforts towards a standardization shall start

Round Robin tests shall be in place

E. Wakai et al., Po 1-83
DEVELOPMENT STATUS OF SMALL SPECIMEN TEST TECHNIQUE IN IFMIF/EVEDA
Design of the Li target implements the lessons learnt throughout 30 years of studies.

Bragg’s peak in Li of 40 MeV at 19 mm
25 mm thick screen +/-1 mm perturbations

Power density of 1 GW/m² (beam footprint maximized)
~x10 lower than FMIT

Concave back plate leads to kPa centrifugal pressures

Maximum pressure waves amplitudes of 32 Pa

15 m/s liquid Li speed evacuate the beam power

\[ V_{\text{max}} = 0.5 \text{ m/s} \] of wave pressure prevents resonances

\[ \Delta T = 41 \text{ K} \]

\[ T_s \] corresponding to the centrifugal pressure

\[ T_{\text{max}} \] in the liquid lithium

\[ \Delta T = 41 \text{ K} \]

2 x 125 mA d⁺ @ 40 MeV
Lithium flowing at 15 m/s

\[ T_{\text{max}} \] envelope in the beam footprint under nominal conditions at different depths (in green) vs \( T_s \) corresponding to the centrifugal pressure in the flowing lithium (in red). 615 K corresponds to the beam line pressure of 0.001 Pa.

**Fig. 4.** \( T_{\text{max}} \) in the beam target interaction of IFMIF: state of the art, Fusion Engineering and Design 89 (2014) 1709–1716

Demo performance seems to be less ambitious than in 2007.

World fusion roadmaps talk of MW in the grid in the 40s.

Do we need IFMIF?

>20 dpa/fpy
Are beam footprint of 200 x 50 mm$^2$ and 40 MeV deuteron energy definitive?

An assessment of available volumes vs dpa with different beam footprint and energy has been carried out.

![Graph showing damage dose vs volume for different beam footprints and energies.](image)

Thanks to Angel Ibarra

<table>
<thead>
<tr>
<th>Deuteron energy</th>
<th>n spectrum broad peak</th>
<th>Bragg peak</th>
<th>Relative cross section $^{56}$Fe($n,\alpha$)$^{53}$Cr</th>
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<td>9 MeV</td>
<td>~4</td>
<td>1</td>
<td>2.5 x $10^3$</td>
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<td>26 MeV</td>
<td>~10</td>
<td>7</td>
<td>0.5</td>
</tr>
<tr>
<td>40 MeV</td>
<td>~15</td>
<td>19</td>
<td>1</td>
</tr>
</tbody>
</table>

Careful assessment in future publication

F. Mota et al., Sensitivity of IFMIF-DONES irradiation characteristics to different design parameters, Nuclear Fusion (2016)
A Li(d,xn) yes, but less ambitious

Ideas for a simplified version

One only accelerator

DONES in Europe

A-FNS in Japan

are maturing

Decisions are likely to happen in 2016
A-FNS plans are to construct it in Rokkasho.
A-FNS plans are to construct it in Rokkasho

LIPAc energy will be increased to 40 MeV

ELTL will be adapted to A-FNS
Japan is moving...

14 MeV neutrons available by 2027

Fig. 1. Roadmap of the fusion energy development in Japan, where usage of the fusion power will be realized by 2050’s.
Europe’s Fusion Roadmap states that irradiation studies up to ~30 dpa with a fusion neutron spectrum are needed before the DEMO design can be finalised.

EDA phase of EVEDA is finished WPENS project in the framework of the EUROfusion activities is continuing design activities

Three candidates a decision on the site is wished during 2016
But also Europe is moving...

**DONES**

125 mA at 40 MeV

VS

**ENS**

125 mA at 26 MeV

*(idea abandoned)*

An agreement seems to have been found for DONES

Within 8 years from decision we could have 14 MeV neutrons

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The EDA Phase was successfully accomplished on schedule

IFMIF nominal flow operational conditions of liquid lithium have been validated

IFMIF HFTM design has been validated

LIPAc commissioning is advancing in Rokkasho
125 mA in CW 40 MeV deuteron accelerator is nowadays at hand of technology

The on-going success of IFMIF/EVEDA allows four decades after the seminal ideas the construction of a Li(d,xn) fusion relevant neutron source adapted to fusion community needs

for a marginal cost of a fusion reactor
Thanks to the EU-JA IFMIF family (and all people involved in former phases/projects) for their resilient enthusiasm crucial for the present success of the program

and thanks to you for your attention