The RFQ for IFMIF-EVEDA project: status and high-power tests.

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International Road Map
Advanced Materials are at a critical path

ITER

1-3 dpa/lifetime

Plasma Facing Materials
Structural Materials
Functional Materials

DEMO

< 150 dpa

IFMIF

20-40 dpa/year

Dpa: displacement per atom; measure the integral of received radiation

International Fusion Materials Irradiation Facility
IFMIF Principles

Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

Accelerator
- Deuteron accelerators:
  - 2 x 125 mA D⁺ CW at 40 MeV

Target
- 10 MW beam heat removal with high speed liquid Li flow
- Irrad. Volume > 0.5L for 10¹⁴ n/(s·cm²), (20 dpa/year)
- Temp.: 250<T<1000°C

Test Modules
- n-irradiation (~10¹⁷ n/s)
- PIE

Typical reactions:
- ⁷Li(d,2n)⁷Be, ⁶Li(d,n)⁷Be, ⁶Li(n,T)⁴He

Beam footprint on Li target
- 20cm wide x 5cm high
- (1 GW/m²)
A specific source is needed to simulate DEMO

- The accumulation of gas in the materials lattice is intimately related with the neutron energy
  - $^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$
  - (incident n threshold at 2.9 MeV)
  - and
  - $^{54}\text{Fe}(n, p)^{54}\text{Mn}$
  - (incident n threshold at 0.9 MeV)
  - Swelling and embrittlement of materials takes place

Neutron flux compared with DEMO’s in available and planned neutron sources

Steven J. Zinkle, A. Moeslang, Evaluation of irradiation facility options for fusion materials research and development, Nuclear Engineering & Design, pre-printed (2013)
Example of after irradiation test of small specimens

Fatigue:

<table>
<thead>
<tr>
<th>$\varphi$ [mm]</th>
<th>1.25</th>
<th>1.25</th>
<th>1.25</th>
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<tbody>
<tr>
<td>$\rho$ [mm]</td>
<td>10</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>$\varphi/\rho$</td>
<td>0.125</td>
<td>0.500</td>
<td>1.000</td>
</tr>
<tr>
<td>$K_t$</td>
<td>1.03</td>
<td>1.11</td>
<td>1.21</td>
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</tbody>
</table>

Different shape specimens for fatigue tests
Facility design
Accelerator facility of IFMIF

- The highest intensity
- The highest beam power
- The highest space charge
- The longest RFQ

2 x 5 MW beams

Individual availability of >90%

D⁺ source
CW 140 mA 100 keV

RFQ
175 MHz 5 MeV

SRF Linac
HWR 175 MHz 40 MeV

2 accelerators, 2 x 125 mA, 2 x 5MW

Beam shape
200 x 50 mm²
Linear IFMIF Prototype Accelerator

Being installed and commissioned in Rokkasho

J. Knaster et al., Installation and Commissioning of the 1.1 MW deuteron prototype Linac of IFMIF
IPAC 2013 Shanghai
### RFQs general parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Lab</th>
<th>ion</th>
<th>energy</th>
<th>voltage</th>
<th>current</th>
<th>power</th>
<th>Freq.</th>
<th>length</th>
<th>Emax</th>
<th>Ave</th>
<th>Max</th>
<th>Power density ave</th>
<th>Power density max</th>
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</thead>
<tbody>
<tr>
<td>IFMIF EVEDA</td>
<td>LNL</td>
<td>d</td>
<td>2.5</td>
<td>79-132</td>
<td>130</td>
<td>650</td>
<td>585</td>
<td>175</td>
<td>9.8</td>
<td>5.7</td>
<td>1.8</td>
<td>3.5</td>
<td>60</td>
</tr>
<tr>
<td>The RFQ is INFN Italy responsibility</td>
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</table>

LNL
Padova
Torino
..Bologna

The RFQ is INFN Italy responsibility

- **Cryo pump**
- **RF coupler**
- **Tuner**

**IFMIF-EVEDA RFQ**
- 18 modules 9.8 m
- Powered by eight 220 kW rf chains and 8 couplers
- High availability 30 years operation.
- Hands on maintenance
- First complete installation in Japan

**0.55 m module**
RFQ system organization

- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti

About 30 persons involved, 20 FTE, 10 dedicated contracts

The participation of INFN to IFMIF-EVEDA includes
- RFQ construction
- Participation to final IFMIF design activity
- Participation to the man power of the project team in Japan
- Participation to beam commissioning in Japan
IFMIF/EVEDA Accelerator building by JAEA (Rokkasho)
The voltage is increased (79-132 kV) following an analytic law

- The focusing in the Gentle Buncher is strong (B=7) so to keep the tune depression above 0.4 for the best control of space charge.
- Main resonances are avoided in the accelerator section
- The focusing in the shaper raises from 4 to 7 to allow an input with smaller divergence.

<table>
<thead>
<tr>
<th>Ions</th>
<th>d</th>
<th>Energy range</th>
<th>MeV</th>
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</thead>
<tbody>
<tr>
<td>input-output nom emitt</td>
<td>0.25 mmmrad (rms)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output long emitt.</td>
<td>0.2 MeV deg (rms)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output current</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>98% WB distr.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% Gaussian distr.</td>
<td></td>
<td></td>
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</tbody>
</table>
Beam losses

- To achieve Beam losses concentrated in the low energy part is very important since neutron production is proportional to $w^2$

$$n = 5.15 \times 10^{-7} Nw^{2.1}$$
650 kW beam should be accelerated with low beam losses and activation of the structure so as to allow hands-on maintenance of the structure itself (Beam losses<10 mA and <0.1 mA between 4 MeV and 5 MeV). (Tolerances of the order of 10-50 um)

600 kW RF dissipated on copper surface: necessity to keep geometrical tolerances, to manage hot spots and counteract potential instability.

The RFQ will be the largest ever built, so not only the accelerator must be reliable, but also the production, checking and assembling procedure must be reliable
  – Fully exploit INFN internal production capability (design machining, measurement and brazing)
  – Make production accessible for different industrial partners

At present and we are in the production of the modules phase.

9/18 have been accepted today
Modules construction
RF cavities built in three supermodules (6 modules each)

- High energy SM in construction at Cinel, Padua (Italy), Intermediate energy in INFN Padova, Low energy by RI Koln (Germany)
Main news

• Module production:
  – Cinel production completed (6 modules),
  – INFN production, 6/6 final machining, 2/6 brazed (one need repairing).
  – RI electrodes machined, brazing late

• High power tests
  – Segment (four modules) tuned to 175 MHz and ±1%
  – The high power test stand (approx 500 kW installation) is fully operational.
  – The couplers by JAEA have shown unacceptable power losses at the window. As a risk reduction procedure a new couple couplers have been designed and built by INFN (machining and detailed mechanical design at CINEL)
  – INFN couplers have been tested to the nominal power of 200 kW cw
Based on vacuum brazing, LNL mechanical experience with TRASCO, CERN experience for RFQ brazing, design compatible with oven at CERN, LNL and in industry;

Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (length 550 mm).

To minimize the use of Ultra-pure CUC2 and to limit the induced stresses on the raw material, a rough-cut of the shape of the module components from a starting block of about 500x280x570 mm will be performed, by using a EDM (wire electroerosion).

The accelerator is composed by 18 of these modules.
Mechanics details

Head flange

 Vacuum grids machined from bulk
Cooling circuit

• About **600 kW RF power** are removed by means of **28 channels** longitudinally drilled along the RFQ modules; the water velocity is approximately 3 m/s,

• **12 channels at fixed low temperature** on the vanes

• **16 channels on the cavity wall** with variable temperature for **frequency tuning**

• the temperature of the channels on the vane and on the cavity wall can be separately tuned so to achieve a tuning range of **±100kHz**.

• 3 modules are in series (**supermodule**)
3D details

- Dummy tuners, vacuum grids and end cells
- In the end cell the 45° angle of the undercut guarantees the access of the cooling channel as close as possible to the hot spot at the electrode base (~80 W/cm²), which is the most severe of the entire RFQ
- Deformations of 70 um and field perturbation less than 1%

*with margin of 10% higher field

Slug tuners (CF100)

Tuning range ±1 MHz

70 deg C
100° Congresso Nazionale SIF
First construction step module n. 16

- Rough machining of block 550 mm long via EDM for minimal stresses and deformations during annealing and brazing

EDM at Padova

Remaining copper

550 mm electrode before cleaning
Finishing

- 0.7 µm roughness
- 3D modulation
- 20 µm tolerances on vane tip geometry
Four electrodes of module #16 electrodes (machined by Cinel) in specs

Max Deviation: 18.6 µm

Max Deviation: 10.5 µm

Max Deviation: 6.1 µm
INFN development for Brazing

Necessary for the large production (18 modules could not be done at CERN).

Vacuum oven in INFN LNL
Brazing at LNL (1/2)

- Upgrade of the vacuum system
- Construction of the assembly lab
- Test of brazing geometry with test pieces.
- Ultrasonic check of brazing
Brazing at LNL (2/2)

- Chemical preparation
- Brazing
Successfull Brazing at LNL and Cinel of two small prototypes (half scale transversally)

- Construction of the assembly lab
- One step vertical
- Ultrasonic check of brazing
- Chemical preparation
- Brazing
- Vacuum ok dimensions not significative
Module 16 brazing

After first brazing (Vertical, Cinel) vacuum and dimensions were ok

After second brazing (Vertical)

Vacuum leak repairing on vacuum port and severe problems with brazing of head flange plates. Deformation at the limit of PA acceptance (100 um, 1 MHz)
- Machining and QA at INFN Padova
- Chemical processing at LNL
- Assembly at LNL (sez pd responsibility)
- Brazing by LNL
High power test stand at LNL

- A 500 kW test stand able to test 4 RFQ modules, to test at full power density the structure (200 kW RF power)

- The test is necessary to validate the design during the module construction (it was ment to be used at the beginning, now we have built half of the modules)
• All the components for coupler test-stand arrived to LNL at the beginning of July 2013.

• Before connecting the system to the RF line, a Network Analyzer was used to measure RF properties.

• Couplers resulted to be underperforming: 25% power losses
A new RF Power Coupler was designed
A new coupling cavity was designed
Two new RF windows were ordered and delivered to LNL
The two couplers were machined (CINEL) and brazed (LNL)
The new coupling cavity was produced (CINEL)
A new coupler test-stand was assembled
Coupler conditioning started

<table>
<thead>
<tr>
<th>Status</th>
<th>Input power (kW)</th>
<th>Duty Cycle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27/05/2014</td>
<td>200</td>
<td>0.02</td>
</tr>
<tr>
<td>28/05/2014</td>
<td>200</td>
<td>2.50</td>
</tr>
<tr>
<td>29/05/2014</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>03/06/2014</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>
Power Coupler - Concept

- Coupler and RF window are two separate devices coupled with a standard 6-1/8 IEC coaxial interface
- Coupler material is copper OFHC
- Water heat exchange coefficient is maintained near 10000 W/m²K in the whole heat exchange surface: water velocity is above 2.5 m/s both in the external and internal spiral and in the loop
- Coupler inner connection is used to remove power from the RF window
HPC – Machining and brazing
High Power Couplers
S\textsubscript{12} = -0.34 dB (7.6% insertion loss) (with dummy couplers)
S\textsubscript{12} = -0.44 dB (9.7% insertion loss) (with final couplers without joints)
HPC test-stand control system
RFQ alignment (outside view)
1. Tuner flush and end plates @ nominal settings (g=12 mm insertion each): Mode Spectra

Q modes
fq0=174.77 MHz
fq1=190.79 MHz
fq2=226.52 MHz
Q0 (fq0) = 7040

D modes
fd0=171.38 MHz (degeneracy= 10 kHz)
fd2=190.86 MHz (degeneracy= 30 kHz)
fd2=228.68 MHz (degeneracy= 50 kHz)

Beadpull measurements (metallic bead)
Dipole components are very low:
Strong Q component tilt at LE side
Due to the P2 module frequency mismatch
3. Measurement after 2 tuning steps

fq₀ = 175.014 MHz

The attainment of the maximum value of ± 2% voltage perturbation is verified almost everywhere in the RFQ. The zone exceeding this value is related only to the P2 RF plug.

4. Measurement after the insertion of the dummy coupler

fq₀ = 175.001 MHz

The dummy coupler had only a very slight effect on both fq₀ and voltages.
Thank you