LIPAC, THE IFMIF/EVEDA PROTOTYPE ACCELERATOR: ALIGNMENT AND ASSEMBLY
CURRENT STATUS AND POSSIBLE FUTURE IMPROVEMENTS

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IWAA 2016
October 2016
ESRF Grenoble
The first wall of the reactor vessel shall absorb neutrons energy.

ITER first wall will present $3 < \text{dpa}$ at the end of its operational life.

In a Fusion power plant, $\sim 30$ dpa per year of operation.

Two transmutation reactions become critical:

- $^{56}\text{Fe}(n,\alpha)^{53}\text{Cr}$
- $^{56}\text{Fe}(n, p)^{56}\text{Mn}$

with $n$ threshold energies at 2.9 and 0.9 MeV.
The necessity of a Fusion relevant n source

Understanding the degradation of physical properties of the materials critically exposed to 14.1 MeV n flux is a key parameter to allow accomplishment of the design of a fusion power plant and its licensing.

Fluences in ITER will be reduced. ITER’s objective is to show stable plasma operation under DT fusion reactions.

But future power plants will have to show this stable operation for long periods with minimum preventive maintenance interventions.

Material scientists need experimental data given the number of variables playing a primary role in materials degradation: neutrons spectrum, neutrons fluence, material temperature, thermo-mechanical history, microstructure, mechanical loading, lattice kinetics...

Neither fission reactors (0.3 He/dpa) nor spallation sources (>50 He/dpa) give needed answers.

Fusion relevant neutron source is indispensable.
Signed in February 2007
Entered into force on June 2007

IFMIF
International Fusion Materials Irradiation Facility

EVEDA
Engineering Validation & Engineering Design Activities

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
A flux of neutrons of $\sim 10^{18}$ m$^{-2}$s$^{-1}$ is generated in the forward direction with a broad peak at 14 MeV and irradiate three regions:

- $>20$ dpa/y in 0.5 liters
- $>1$ dpa/y in 6 liters
- $<1$ dpa/y in 8 liters

Availability of facility $>70\%$
**Validation Activities – EVA phase**

**D⁺ Accelerator**
- Incident current: 2 x 125 mA CW

**Lithium Target**
- Thickness: 25 ±1 mm
- Flow speed: 15 m/s

**High Flux Test Module**
- 12 capsules (>1000 specimens)
- 250 °C < \( T_{\text{CAP}} < 550 °C \)
- +/-3% \( \Delta T \) per capsule

**Additional Information**
- IFMIF: overview of the validation activities, *Nuclear Fusion* 53 (2013) 116001
- J. Knaster et al., *IFMIF: overview of the validation activities*
D⁺ Accelerator

incident current 2 x 125 mA CW

LEBT  RFQ  MEBT

100 keV  5 MeV  9 MeV  14.5 MeV  26 MeV  40 MeV

RF Power

Superconducting cavities

HEBT

Test Cell

H  M  L

Lithium Target

Thickness 25 ± 1 mm

Flow speed 15 m/s

140 mA CW

IFMIF

LIPAc

EVA Phase – Accelerator facility

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IFMIF

LIPAc

40 MeV

125 mA

5 MW

1.125 MW

9 MeV

125 mA

250 oC < TCAP < 550 oC +/−3%

Δ T per capsule

140 mA CW

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LIPAC, the accelerator of records

LIPAC is very ambitious

- World’s highest current linac
- World’s top H⁺&D⁺ injector performance
- World’s longest RFQ
- World’s record of light hadrons current through SC cavities
- World’s highest beam perveance

P. Cara et al.
The Linear IFMIF Prototype Accelerator (LIPAc) design development under the European-Japanese collaboration
IPAC 2106 - MOPOY57

J. Wei et al., The very high intensity future, IPAC 2014, Dresde
Equipment designed and constructed in Europe
Installed and commissioned in Rokkasho
LIPAc alignment requirements, why alignment is important

LEDAs reached **100 mA @ 6.7 MeV** at the exit of the RFQ with protons in CW in 1999:
**beam losses mainly due to beam halo**

Beam dynamics calculation on IFMIF accelerator indicates feasibility of nominal performance
**125 mA @ 5 MeV** at the exit of the RFQ + SC accelerating stages

The alignment/learning the position of some components in ± 0.1 mm respect the beam axis is indispensable to contain beam losses to **1 W/m** to minimize components activation and allow hands-on maintenances

**Table 1: Errors distribution**

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Error range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEBT</td>
<td></td>
</tr>
<tr>
<td>Solenoids Misalignment [x,y]</td>
<td>±0.2 mm</td>
</tr>
<tr>
<td>Solenoids Tilt [φx, φy]</td>
<td>±3.5 mrad</td>
</tr>
<tr>
<td>RFQ</td>
<td></td>
</tr>
<tr>
<td>RFQ Segment Misalignment [x,y]</td>
<td>±0.1 mm</td>
</tr>
<tr>
<td>RFQ Voltage (first harmonic shape)</td>
<td>±2 %</td>
</tr>
<tr>
<td>RFQ Mean Radius</td>
<td>±20 μm</td>
</tr>
<tr>
<td>RFQ Vane Radius</td>
<td>±20 μm</td>
</tr>
<tr>
<td>MEBT</td>
<td></td>
</tr>
<tr>
<td>Quadrupoles Misalignment [x,y]</td>
<td>±0.2 mm</td>
</tr>
<tr>
<td>Quadrupoles Tilt [φx, φy]</td>
<td>±10 mrad</td>
</tr>
<tr>
<td>Buncher cavities Misalignment [x,y]</td>
<td>±1 mm</td>
</tr>
<tr>
<td>Buncher cavities Tilt [φx, φy]</td>
<td>±30 mrad</td>
</tr>
<tr>
<td>BPMs Measurement Accuracy</td>
<td>±0.1 mm</td>
</tr>
<tr>
<td>SRF linac</td>
<td></td>
</tr>
<tr>
<td>Resonators Misalignment [x,y]</td>
<td>±2 mm</td>
</tr>
<tr>
<td>Resonators Tilt [φx, φy]</td>
<td>±20 mrad</td>
</tr>
<tr>
<td>Resonators Field amplitude</td>
<td>±1 %</td>
</tr>
<tr>
<td>Resonators Field phase</td>
<td>±1 deg</td>
</tr>
<tr>
<td>Solenoids Misalignment [x,y]</td>
<td>±1 mm</td>
</tr>
<tr>
<td>Solenoids Tilt [φx, φy]</td>
<td>±10 mrad</td>
</tr>
<tr>
<td>BPMs Measurement Accuracy</td>
<td>±0.25 mm</td>
</tr>
<tr>
<td>HEBT</td>
<td></td>
</tr>
<tr>
<td>Quadrupoles Misalignment [x,y]</td>
<td>±0.2 mm</td>
</tr>
<tr>
<td>Quadrupoles Tilt [φx, φy]</td>
<td>±15 mrad</td>
</tr>
<tr>
<td>Quadrupoles Tilt [φz]</td>
<td>±3 mrad</td>
</tr>
<tr>
<td>Dipole Misalignment [x,y]</td>
<td>±1 mm</td>
</tr>
<tr>
<td>Dipole Tilt [φx, φy, φz]</td>
<td>±10 mrad</td>
</tr>
<tr>
<td>BPMs Measurement Accuracy</td>
<td>±0.1 mm</td>
</tr>
</tbody>
</table>


N. Chauvin et al., *Start-To-End beam dynamics simulations for the prototype accelerator of the IFMIF/EVEDA Project*, IPAC 2011
• **LEICA AT401 Laser Tracker:**
  • MPE angle accuracy ±(16µm+5µm/m), MPE distance accuracy: ±10 µm, level accuracy: ± 1 arcsec;

• **Spatial Analyzer Ultimate metrology software:**
  • Experience of F4E Metrology team
  • Capability of estimate the uncertainty of measurements through USMN algorithm
  • Capability of simulations of measurements to optimize measurement process;
  • Verification of instrument performance in the real environment
According to F4E QA metrology handbook, the ratio between tolerance and target measurement uncertainty shall be above 5.

SA simulations with USMN were performed to design the position and number of fiducials in the vault.

130 fiducials were placed on the floor and walls of the vault.

Real vs simulated measurements $2\sigma$
Uncertainty plot
Rokkasho enjoys hard winters and hot summers.

In the simplest case, for a structure of uniform material, uniform temperature distribution, absence of restraints, a linear model shall be enough accurate to model its thermal expansion. A simple procedure to study and eventually compensate the effect of thermal expansion of the building.

Weekly measurement by LT in ADM mode the distance between points on the floor and walls.

Weekly measurement of the air temperature in the vault and external temperature.

Weekly measurement the temperature on 30 points evenly spread on the floors and walls.

Monitoring continued on a period including at one winter one summer.

<table>
<thead>
<tr>
<th>Date</th>
<th>T floor [°C]</th>
<th>T air [°C]</th>
<th>FL1-FL48 Dist [mm]</th>
<th>Nom. Dist [mm]</th>
<th>Meas. Dist [mm]</th>
<th>USMN Measured Delta [mm]</th>
<th>Scale factro to USMN alfa [m/°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014.05.02</td>
<td>23562.744</td>
<td>23562.107</td>
<td>-0.187</td>
<td>0.999973</td>
<td>13</td>
<td>800.001</td>
<td>0.999973</td>
</tr>
<tr>
<td>2014.05.08</td>
<td>23562.744</td>
<td>23562.184</td>
<td>-0.56</td>
<td>0.999976</td>
<td>13.5</td>
<td>800.001</td>
<td>0.999976</td>
</tr>
<tr>
<td>2014.05.20</td>
<td>23562.744</td>
<td>23562.37</td>
<td>-0.374</td>
<td>0.999984</td>
<td>14.6</td>
<td>800.005</td>
<td>0.999984</td>
</tr>
<tr>
<td>2014.07.09</td>
<td>23562.744</td>
<td>23562.986</td>
<td>0.242</td>
<td>1.000010</td>
<td>19.5</td>
<td>800.009</td>
<td>1.000010</td>
</tr>
<tr>
<td>2014.07.24</td>
<td>23562.744</td>
<td>23563.151</td>
<td>0.407</td>
<td>1.000017</td>
<td>20.7</td>
<td>800.01</td>
<td>1.000017</td>
</tr>
<tr>
<td>2014.08.01</td>
<td>23562.744</td>
<td>23563.332</td>
<td>0.588</td>
<td>1.000025</td>
<td>21.8</td>
<td>800.01</td>
<td>1.000025</td>
</tr>
<tr>
<td>2014.09.30</td>
<td>23562.744</td>
<td>23563.595</td>
<td>0.851</td>
<td>1.000036</td>
<td>24.0</td>
<td>800.012</td>
<td>1.000036</td>
</tr>
</tbody>
</table>

Unfortunately we discovered that a linear model to compensate the thermal expansion effect of the vault was not enough accurate to satisfy the uncertainty thresholds for the alignment of the components and FEM analyses may result complicated to be developed. It resulted to be highly recommendable to re-measure and redefine the coordinates of vault metrology network periodically especially before a precise alignment or survey of the components respect the beam line frame is needed.
RFQ alignment and assembly

CMM fiducialization@ INFN

L. Ferrari et al., “IFMIF RFQ Module Characterization via Mechanical and RF Measurements”, Proceedings of LINAC2016, East Lansing, Michigan, USA.

E. Fagotti et al., “Preparation and Installation of IFMIF-EVEDA RFQ at Rokkasho Site”, Proceedings of LINAC2016, East Lansing, Michigan, USA.

SMs assembly @ INFN LNL
Since the phase A commissioning is still ongoing, the RFQ after arrival at Rokkasho was installed in a temporary position shifted 1 SM length along the beam line in the vault to allow RF tuning operations during the injector shut downs. In this way it was possible to test the feasibility of alignment and assembly of the RFQ SMs and avoid potential delays in the schedule of installation and commissioning in Rokkasho.

SM1 alignment

SM1-SM2 connection preparation

SM2 alignment

SM2-SM3 connection

SM3 alignment

SM1-SM2 connection

P. Mereu et al., “Mechanical integration of the IFMIF-EVEDA radio frequency quadrupoles”, Proc. of IPAC2016, Busan
The alignment campaign of the RFQ SMs performed in the temporary position @ IFMIF/EVEDA site showed the feasibility of the assembly.

- The beam axis at the interface of the SMs connection were matched with a precision below 60 μm in transverse direction.
- The beam axis at the entrance and exit of the RFQ were transversally aligned with a precision below 50 μm.
- The 2σ USMN estimated fiducials measurement uncertainty was below 30 μm.
A fruitful collaboration was established between F4E metrology team, ILIC metrology team and CIEMAT MEBT and DPlate teams to tackle and optimize as much as possible the alignment and assembly aspects (e.g.: determination of number and position of the fiducials, procedures to be followed, etc.). SA simulations were extensively used to support the design of the alignment process.

In order to prevent potential delays on the installation and commissioning of the accelerator in Rokkasho, alignment and assembly alignment campaigns were organized at CIEMAT premises to test the feasibility of the alignment and assembly within the design tolerance requirements.

Before the alignment respect the MEBT and Dplate frame, all the components that needs alignment were characterized by means of CMM. Magnetic measurements were performed to determine and compensate the magnetic respect mechanical axis deviations.
Limited space around the MEBT assembly and visibility of tracking alignment keypoints that would require several changes of tracker station, 2 laser trackers (one Leica AT960 + T-probe and one Leica AT402) were used in parallel.
After the assembly and alignment of the components of the MEBT was completed, all the fiducials were surveyed by different station. More than 80 fiducial nests have been surveyed many times realizing a database of more than 500 measurements. For the adopted process and layout, the 2σ uncertainty of each fiducial was below 20 μm along each transversal and longitudinal directions. The analyses of the data confirmed the feasibility of the alignment of the MEBT components below ±0.1 mm respect the MEBT beam line frame, within the required tolerances.
After shipment to Rokkasho, the MEBT was installed in a temporary position on the beam line in the accelerator vault.
The survey of the fiducials performed last summer showed the magnet center positions were out of alignment tolerances (up to 0.6 mm in horizontal direction)
Due to different hardware availability, one Leica AT401, the process resulted to be quite time consuming (one month and half was spent) and some difficulties were encountered: e.g.: the BPMs would require several iterations from different laser tracker stations. it was decided to mechanically assemble them by means of calibrated gauges and survey their fiducials to determine their center position and tilting respect the MEBT frame.
As for the MEBT also the Dplate was surveyed at CIEMAT premises before the shipment to Rokkasho with F4E metrology team collaboration.

1) The process started with the definition of the Dplate beam coordinate frame surveying features and nests of the frame
2) The heaviest components were (circled in yellow and green) were firstly aligned
3) Than the BPMs were aligned
4) After the assembly and alignment has been completed, all the nests were surveyed by different laser tracker stations. All the components resulted to be aligned with a precision below 50 µm in transversal direction and the 2σ target uncertainty estimated by USMN resulted to be 20 µm max. along each direction.
As RFQ and MEBT, also the Dplate after shipment was installed in a temporary position along the beam line to carry out assembly phases during injector shut down time. A survey of the Dplate fiducials was performed last summer. A realignment campaign is needed and scheduled at beginning of 2017. The BPMs position is out of tolerance and realignment is needed. Some diagnostics may require smaller tolerances according to new calculations performed by beam dynamics group.
• Needs of periodically check the beam line components alignment
• Although the PG setup of instrumentation and target may be time consuming, it should considerably reduce time required for the survey (minimizing impacts on the commissioning schedule and personnel exposure to ionizing radiations).
• Possibility to share the target nests and easily implement new PG targets.
• PG software is compatible with SA.
• Recent tests performed on a ITER components by ITER metrology team to compare LT and PG, gave same uncertainty results, around 0.02 mm.
Conclusions

• Deformations of the vault induced by thermal effect at the moments can only be treated in the same way as deformations induced by earthquakes/load of components, i.e. a survey and redefinition of the coordinates of the metrology network through USMN is needed.

• The alignment campaigns performed at labs and IFMIF/EVEDA vault on the RFQ, MEBT and Dplate demonstrated the feasibility of the alignment of each subsystem within the design tolerances respect the beam line frame. The components are ready for the integration for the phase B commissioning.

• The experience with the realignment of the MEBT with only one AT401 recommends the use of a second laser tracker (e.g.: AT960 + T-probe) to improve the quality and increase the speed of the alignment process.

• The promising results obtained with photogrammetry technique by F4E metrology team gave positive indications on its implementation on the monitoring of the components inside the IFMIF/EVEDA vault.
Thanks a lot for your attention