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

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Abstract

IFMIF (International Fusion Material Irradiation Facility) will be a Li(d,xn) neutron source providing equivalent neutron spectrum of DT fusion reactions and comparable neutron flux of future commercial reactors. Such a facility is an essential step in world fusion roadmaps to qualify suitable structural materials capable to hold the unrivalled neutron irradiation inside the nuclear vessel of a fusion reactor. IFMIF, presently in its EVEDA (Engineering Validation and Engineering Design Activities) phase is installing LIPAc (Linear IFMIF Prototype Accelerator) in Rokkasho (Japan), a 125mA CW 9MeV deuteron beam as validating prototype of IFMIF accelerators. Beam dynamics calculations demand accuracies of alignment within ± 0.1 mm respect the beam line frame inside an assembly hall of about 8x40 m^2 to keep beam losses and allow future hands-on maintenance activities. A metrology network was designed and installed to guarantee a target measurement uncertainty of 20 μm at 2σ to satisfy a ratio above five between alignment tolerance and measurement uncertainty, according to F4E QA metrology handbook. In order to optimize installation schedule and reduce as much as possible potential risk on the alignment process, we decided to test and validate the assembly and alignment requirements of each subsystem whenever possible before the delivery to Japan.

The results of these campaigns regarding the components needed for the next LIPAc beam commissioning phase B (the beam will be transported from the injector to a low power beam dump through the LEBT, RFQ, MEBT and DPlate), as well as some potential improvements related with the utilization of photogrammetry technique and displacement sensors to monitor all the accelerator line will be presented in this paper.

IFMIF AND LIPAc, ITS PROTOTYPE ACCELERATOR

Fusion materials research has fuelled for decades the world endeavours towards high current linacs [1]. The required neutron flux >1018 m2·s-1 with a broad peak at 14 MeV to simulate the irradiation conditions of the plasma facing components in a fusion reactor is obtainable through Li(d,xn) stripping reactions. The first world attempt of such conditions was framed by the Fusion Materials Irradiation Test Facility, FMIT, in the early 80s; with unexpected difficulties and lessons learnt in operating in CW mode [2]. The International Fusion Materials Irradiation Facility, IFMIF, consists of two deuteron accelerators at 125 mA in CW and 40 MeV impacting on a flowing lithium screen (Figure 1). It is since 2007, in its Engineering Validation and Engineering Design Activity phase, EVEDA, where the only remaining activity of its broad mandate (that has provided an engineering design [3] of the plant and, among many other technical challenges, validated the stable operation of its lithium loop [4] and its irradiation modules capable of housing above 1000 specimens and characterize structural materials simultaneously in twelve different irradiation capsules independently cooled [5]) is its Linear IFMIF Prototype Accelerator, LIPAc, presently under installation and commissioning in the International Fusion Energy Research Center (IFERC) in Rokkasho (Japan), by European and Japanese laboratories [6] (Figure 1). A full account of the validation activities under IFMIF/EVEDA has already been provided [7].

Collective phenomena driven by space charge forces become the main limitation on achieving high intensity beams. In low β regions, the beam outward radial Coulomb forces prevail over the inward radial Ampere ones, but they mutually cancel in the relativistic domain. Thus, the lower the beam energy is, the stronger the space charge repulsive forces are.

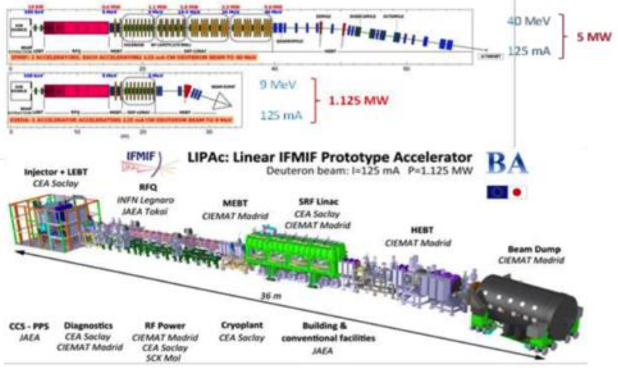

Figure 1: Above - Comparison of IFMIF accelerators and LIPAc, their 1.125 MW beam average power prototype

accelerator, matched up to the 1st SRF linac at 9 MeV. Below - breakdown of the contribution for LIPAc.

The involved high power and beam nature entails investment protection arguments and radiation safety aspects. The study of LIPAc and IFMIF accelerator's beam losses has been a matter of various publications, the most recent one is [8]. Due to high energy and current of the beam and the long path from the source to the target, a very high precision in the mechanical alignment between the components is a key point to contain beam losses below 10^{-6} and 1 W/m, reduce consequent activation and allow hands-on maintenance of the components.

The successful operation of LIPAc, with its deuteron beam current of 125 mA in CW at 9 MeV as the output of the first planned cryomodule of IFMIF will validate the 40 MeV required for the Li(d,xn) source [1,9].

COMMISSIONING PHASES OF LIPAc

The installation and commissioning of LIPAc is organized in four different phases.

- In the first phase, called phase A and currently ongoing, a 125 mA D+ beam up to CW is extracted from an ion source, accelerated to 0.1 keV and transported through a Low Energy Beam Transport (LEBT) up to a beam stopper.
- In the second phase, called phase B, a D+ 125 mA, 0.1% DC max beam at the exit of the LEBT is accelerated up to 5 MeV by a RadioFrequency Quadruople and transported through a Medium Energy Beam Transport and a series of diagnostic devices (DPlate) up to a low power beam dump.
- In the third (phase C) and fourth (phase D) phases the D+ beam at the exit of the MEBT will be input and accelerated from a Superconductive RadioFrequency LINAc and transported through a High Energy Beam Transport (HEBT) up to a high power beam dump. The diagnostics components used during phase B will be moved and integrated in the HEBT. In phase D the DC of the 125mA D+ beam will be increased up to CW for a total power of 1.1 MW.

ALIGNMENT METROLOGY NETWORK IN THE ASSEMBLY HALL AND INSTRUMENTATION

The design of the metrology network in the assembly hall has been already described in a paper already published in the last IWAA 2014 [10]. The required alignment tolerance budget of the components is in the order of ±0.1 mm for some components are typical for the use of laser tracker instrumentation. At the moment the metrology team is equipped with a Leica AT401 laser tracker and Spatial Analyzer (SA) Ultimate metrology software. 130 fiducials (see Figure 1) are randomly placed in the assembly hall to meet the uncertainty requirements.

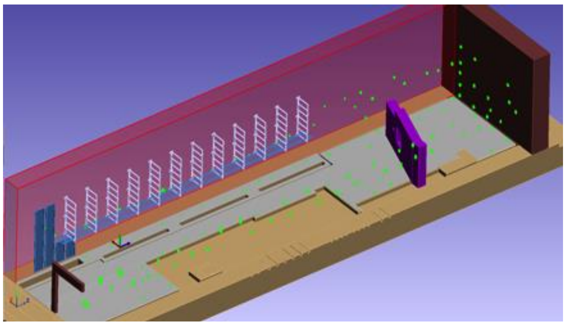

Figure 1 Position of the 130 fiducials on accelerator assembly hall of 8x40 m at Rokkasho site.

Since the accelerator facility is located in a place that, in addition to possible strong earthquakes, suffers of cold winters and hot summers the impact of the temperature variation of the building was studied.

In the most simple case considering structure of uniform material and temperature distribution, a linear model is enough to model its thermal expansion. In case of a large structure like a building, the thermal expansion effect may result quite complex to be modelled and compensated (e.g.: presence of thermal gradients, constraints on the deformations, etc.) involving extensive use of FEM simulations [11, 12].

A procedure has been established. It was decided to monitor weekly the temperature distribution on the floor and walls of the assembly hall and measure distances between points exploiting the ADM of the laser tracker for a period including at least one summer and one winter.

While the deviations of temperature on various points on the walls and the floor was not so significant (± 2°C) respect the average each week, a difference on the average in the order of 10 °C between winter and summer was registered.

Unfortunately it resulted that it was not possible to use linear scaling to model the deformation of the building induced by the thermal effect, the uncertainty resulting above the acceptable threshold. In addition to the surveys of the network after strong earthquakes or installation of heavy components, it is highly recommended to remeasure and redefine the coordinates of the fiducials through the USMN of SA on the assembly hall periodically (e.g.: each winter and summer) especially before a precise alignment or survey of the components is required.

ALIGNMENT OF PHASE B COMPONENTS

The alignment and the fiducialization of the injector components was already described in a paper presented at the last IWAA 2014 [10]. In this paper the alignment of the following components for the phase B commissioning will be described: the RFQ, the MEBT and Dplate and Low Power Beam Dump. The alignment of the components for phase C and D commissioning will most likely published in future since possible improvement and optimization, especially for the SRF Linac, are still in progress.

The RFQ Alignment

The RFQ of LIPAc is composed of 18 modules of about 430 mm x 430 mm transversal section and 550 mm long made of copper and stainless steel flanged together. With a total length of about 10 m, it is the longest RFQ in the world. Beam dynamics simulations [8] require matching the beam axis at the interface of each module within ±0.1 mm. Each module is equipped with 7 nests for the 1.5” SMRs (5 on the face on the top and two on a lateral face). Each module has been fiducialised by means of a CMM at INFN premises [13]. The RFQ was pre-assembled at INFN premises for the shipment to Rokkasho divided in three groups (called “supermodules” (SM)) of 6 modules already connected and aligned by means of a Faro Ion laser tracker (Figure 2).

Figure 2 A supermodule of the RFQ in the assembly phase with the temporary isostatic supports and under vacuum tightness testing.

Each SM is supported to a steel frame by means of a fine adjustable isostatic support [14] following similar principle used for the LHC cryomagnets [15] (circled in yellow in Figure 3). Each foot of the frame, anchored to the floor, provides a mechanism with pushing screws (circled in red in Figure 3) allowing a vertical and horizontal coarse adjustment with a precision of ± 0.5 mm. The RFQ has been installed in a temporary position by shifting it of one SM length along the beam line to allow parallel operations (e.g. RF tuning) during the scheduled shut down periods of the ion source commissioning. In this way it was possible to test the alignment adjustments of the RFQ supermodules and the connection between each supermodule.

Figure 3 Alignment of the SM1 in the temporary position in the assembly hall.

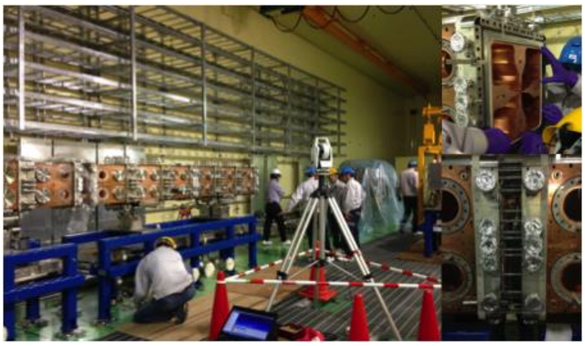

Figure 4 Alignment of SM2 in the Rokkasho on the left vault and detail of the SM1-SM2 interface on the right. The relative alignment between SM1 and SM2 and their position position respect the vault beam line frame were continuously monitored during their connection.

SA simulations were carried out in advance to optimize the metrology process and anticipate potential problems (e.g.: estimate the uncertainty resulting from the process, study the visibility of the fiducials, needs of increase the numbers of the fiducials, etc.). The SM1 was firstly anchored and then aligned to the beam line. Then SM2 was aligned and connected to SM1. Finally SM3 was aligned and connected to SM3.

The fine adjustment isostatic supports system that sustains each of the three SMs independently allowed aligning them respect the beam line frame quite easily and rapidly, although the vertical and horizontal DOFs of the fine adjustment system are coupled. Particular care and continuous monitoring of the position of the module of the RFQ were needed during the connection of the SMs to control misalignments induced by the compression force of the metallic vacuum seal. It is important to notice that the higher priority has been given to the relative alignment of the interface module axis than to align the SMs respect the beam line frame [16]. This means that only the entrance and exit of the RFQ are aligned to the beam line frame, while maximum vertical deviations of the RFQ axis respect the beam line frame in the order of 0.2 mm were registered along the structure. Successful results were obtained in the coupling of the SMs: it was possible 1) to align and connect the modules at the interface of each SMs with a max transversal mismatch of the beam axis of 50 μm; 2) to align the beam axis of both ends of the RFQ with a precision below 50 μm (see Figure 5).

Figure 5 The RFQ after the alignment and connection of the three SMs.

MEBT and DPlate Alignment

A fruitful collaboration was established between F4E metrology team, ILIC metrology team and CIEMAT MEBT and DPlate teams to optimize as much as possible the alignment process (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. Many communications and iterations were required to tackle all the alignment and assembly aspects.

Quality Assurance documents were created for the fiducialization of the components to be aligned and the process to be adopted to allow the assembly of the two subsystems on the beam line.

All of the components that require precise alignment to the beam line were measured and fiducialized respect a local coordinate frame on a CMM.

The coordinates of the fiducials respect the local coordinate frame of the component, the coordinate frame the subsystem and the beam line frame of the accelerator assembly hall with the related alignment tolerances and weights were reported on a common data sheet

Several alignment campaigns involving CIEMAT teams, F4E metrology team and the ILIC team were organized at CIEMAT premises to test the feasibility of the alignment of the MEBT and DPlate subsystems avoiding possible showstoppers and potential delays on the installation and commissioning schedule at Rokkasho BA site.

Concerning the MEBT, it is a very compact structure of about 2.5 m to minimize the space charges issues. Its alignment is a critical part not only for the impact on the beam performances, but also on the mechanical couplings and the vacuum tightness of the line. The components of the MEBT [17] that needs alignment are:

- Five quadrupole magnets (one triplet and one doublet) that integrate also horizontal and vertical steerers to match transversally the beam exiting from the RFQ to the SRF Linac. According to beam dynamics simulations [8], being the tolerance on the transverse positioning respect the beam line frame, ±0.2 mm, the tolerance on the tilting (20 mrad) is automatically satisfied. Magnetic measurements were carried out on each magnet at ALBA premises to determine the position of the magnetic axis [18] and align it to the beam line.
- Two bunchers, one at the end of the magnet triplet and the second at the end of the doublet, to match longitudinally the beam from the RFQ to the SRF Linac. The alignment tolerance is of ±1 mm in transverse position. The tilting tolerances respect the horizontal and vertical axes, being ±30 mrad are automatically satisfied.
- Four Beam Position Monitors attached to the beam pipe and positioned on the poles of the 1st, 3rd, 4th and 5th magnet. The transverse alignment tolerance of the center of the BPMs respect the beam line is of ±0.1 mm.

Each component of the MEBT is independently supported on a steel frame [19]. The vertical and horizontal positions can be adjusted independently (not coupled) by means of a system of fine pitch screws. The feet of the MEBT frame are provided with adjustment screws to allow the alignment of the MEBT subsystem on the accelerator beam line frame.

Due to the limit in space available for the survey, little visibility of key points for alignment two laser trackers were used in parallel to avoid several changes of station and to speed up the process: a Leica AT960 and an AT402 provided by the F4E metrology team. The Leica AT960 was also equipped with a T-Probe, allowing the measurements of points not directly visible by the tracker and speeding considerably the process.

The alignment process started with the definition of the local coordinate frame of the MEBT subsystem. Considering the frame rigid enough and not sensitive to the deformation induced by the gravity load, the components with their supports except the first buncher, were not placed in this first phase to increase the visibility of the points and avoid many changes of laser tracker stations. A series of fiducials were placed on the frame, measured and referred to the local coordinate system through best-fit algorithms. Then the assembly of the MEBT components started. Due to the compact structure, the limited visibility for the tracking of the fiducials and the difficulties to access the adjustments with all the components placed on the frame at the same time, the alignment started from the central and heaviest component, the first buncher. Then each magnet with its support was assembled and magnetically aligned one by one from the center to both ends (see Figure 6).

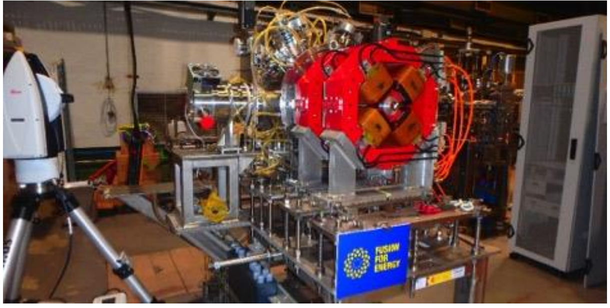

Figure 6 Assembly and alignment of the magnets on the MEBT frame.

During the process it was noticed that projection errors by only tracking the fiducials could lead to potential imprecision on the alignment to the beam line of the centres of the components. This could be solved calculating the position of the centres through best fit of the measured coordinate of the fiducials to the nominal. However this process might be time consuming. A direct method was preferred wherever possible. Since all the components resulted to be machined with good enough accuracy, proper jigs were machined with nests for SMRs to allow direct tracking of the mechanical centres of the components (Figure 6). The contribution to the total uncertainty budget on the measurements of the mechanical centres of the components induced by the jig along each transversal directions is around ±30 μm at 2σ confidence level, compatible with the alignment tolerance requirements.

After the assembly of the magnets on the MEBT frame, each of their top halves was removed to allow the installation of the beam pipe sections that include the BPMs and scrapers (Figure 7). The horizontal and vertical position of the BPMs is adjusted by acting on the support of the scrapers.

Figure 7 Top halves of the magnets disassembled (left) and installation of the scrapers, and beam pipe with BPMs (right).

The alignment and assembly campaign of the MEBT at CIEMAT premises was successfully accomplished in two weeks with positive results. Only the last buncher was missed due to unavailability in the CIEMAT premises. A final USMN survey of the MEBT fiducials (Figure 8) was performed. 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 eah 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.

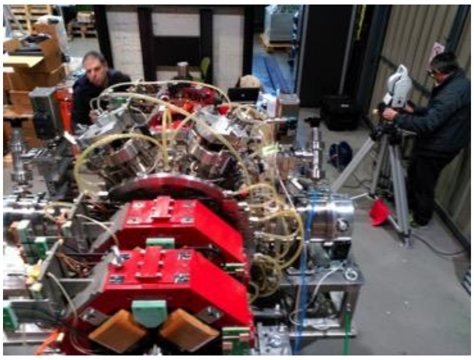

Figure 8 Final USMN survey after the assembly of MEBT was completed.

The MEBT was transported by ship to Rokkasho, located and anchored in a temporary position shifting it along the beam axis in the accelerator vault. A USMN survey of all the fiducials was performed. Misalignments above the beam dynamics tolerances were registered (around 0.6 mm for some magnets) most likely related to the transportation by ship from Spain to Japan.

Another alignment campaign was carried out in Rokkasho this summer. Due to different hardware availability, one Leica AT401, the process was quite time consuming: one month and half was spent while less than two weeks were sufficient at CIEMAT. Due to the limited view of tracking the of the alignment keypoints, some components required iterative changes of tracker stations. Concerning the BPMs the alignment of the centre and tilt respect the MEBT beam line frame was finally abandoned. Being 0.1 mm the clearance between the BPMs and the poles of the magnets, the positioning by adjustment mechanisms was quite difficult and calibrated gauges were used to avoid clashes. The fiducials were surveyed by laser tracker to determine the position of the centre and tilt of each BPM. Taking into account these geometrical data on the RF measurements, it is possible to determine the position of the beam accurately.

Concerning the Dplate [20], it presents 3 BPMs and vacuum chambers housing different types of diagnostics to monitor and control all the necessary beam charateristics (Figure 9).

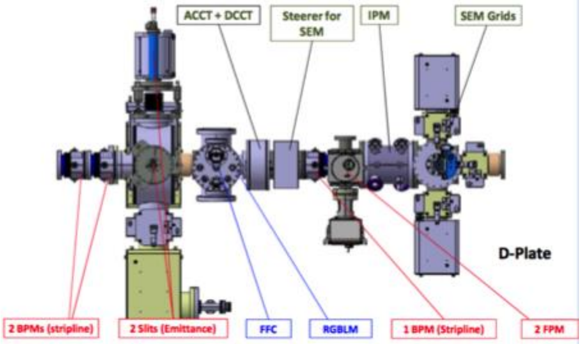

Figure 9 Top view of the layout of the Dplate components.

As for the MEBT, the BPMs shall be aligned respect the DPlate and vault beam line frame with a precision of ±0.1 mm, while 1 mm is enough for the chambers.

Similar to the MEBT each component is independently supported and adjusted respect the support frame and the vertical and horizontal DOFs are decoupled [19]. All the feet of the support frame are provided with vertical and horizontal adjustments screws for the alignment of the DPlate components on the accelerator beam line frame.

A metrology campaign was held at CIEMAT premises involving SETIS Company, contracted by F4E metrology team to demonstrate the feasibility of the alignment and avoid showstopper with consequent potential delays on the installation and commissioning schedule at Rokkasho BA site. The instrumentation used was a Leica AT901 laser tracker equipped with also a T-Probe and Spatial Analyzer metrology software. As for the MEBT, a local metrology network of fiducials was installed on the support frame and the alignment process started with the characterization of the support frame respect the DPlate local coordinate frame. The assembly and alignment process started from the two heaviest components, the chambers with the slits and the SEM grids to minimize potential deformation induced on the support frame. Then the assembly and alignment of the light components started. As for the MEBT, proper tools were precisely machined to directly track the centres of the components and speed the alignment process. The activities for the assembly and alignment at CIEMAT premises were successfully completed in two weeks and the final USMN survey showed that the components were positioned respect the DPlate beam line with a precision of ± 50 µm, well below the alignment tolerances (Figure 10).

Figure 10 The Dplate after the alignment was successfully completed.

The USMN survey of the Dplate fiducials performed at Rokkasho site showed that some misalignments occurred after the transportation from Spain to Rokkasho site and a realignment is needed. Being the visibility of the fiducials and the available space around the Dplate reduced, together with the time consuming experience of the MEBT realignment at Rokkasho site, the realignment of the Dplate is scheduled in the first month of the next year, while more metrology instrumentations should be available.

FUTURE IMPROVEMENTS FOR THE MONITORING OF THE COMPONENTS INSIDE THE VAULT

Due to the needs to periodically check the beam line components alignment, the introduction of photogrammetry (PG) technique in addition to the laser tracker is under consideration. Although photogrammetry may be time consuming for the setup of the scene to be captured and the installation of the targets, it should considerably reduce the time needed for the survey. In this case it could be possible to minimize the impact of the time needed for the survey and the exposure of operators to ionizing radiation resulting from the activation of the components due to beam losses.

Figure 11 Survey with PG technique of ITER PS1 component for ITER project.

Photogrammetry is longer used in Fusion field since decades, for its portability and precision. The photogrammetry technique has been recently adopted and tested in an application in the framework of ITER project giving promising results especially comparing accuracy and uncertainty values to what can be obtained with laser tracker

The use of PG is really an added value for long term repeatable surveys. In all the cases where a metrology network is already present, with some specific tools, it is possible to share the nests and implement easily the new photogrammetry targets. In addition, the software is fully compatible with SA software. On a recent comparison (Figure 11 and 12) campaign using LT Vs PG, the uncertainty on the same targets was similar, typically around 0.02 mm.

Figure 12 Laser tracker survey of the PS1 component for ITER project for comparison with PG.

CONCLUSIONS

The alignment campaigns performed on the RFQ, MEBT and DPlate confirmed the feasibility and the achievement of the tolerances of the assembly of each subsystem. They are ready for the assembly of the accelerator for phase B. However the availability of a second laser tracker, eventually equipped with the T-Probe in addition to the AT401 is recommended to reduce the time of the process and overcome difficulties after the experience on the MEBT. The promising results obtained by F4E metrology team with the photogrammetry technique foresees the possibility of its application on the monitoring of LIPAc accelerator minimizing timing and radiations exposure of the personnel.

DISCLAIMER

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