ALIGNMENT OF LIPAC, THE IFMIF PROTOTYPE HIGH CURRENT DEUTERON ACCELERATOR: REQUIREMENTS AND CURRENT STATUS

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Abstract

IFMIF, presently in its Engineering Validation and Engineering Design Activities (EVEDA) phase, aims at running a 9 MeV / 125 mA / CW deuteron accelerator in Rokkasho (Japan) to validate IFMIF's 40 MeV / 125 mA / CW accelerator with components mainly designed and constructed in European labs. Beam dynamics calculations demand accuracies and precisions of alignment for certain components within ±0.1 mm to keep beam losses below defined thresholds and allow future hands-on maintenance activities. Simulations with the original Global Coordinate Frame (GCF) carried out with Spatial Analyzer® predicted uncertainties in the measurements above the target alignment required precisions. Thus, an upgrade of the original fiducial network was undertaken with the installation of 120 new fiducials and a survey pillar; whose simulations predicted feasible uncertainties of the measurement within x5 of the target accuracies. The survey campaigns carried out with the additional extensive fiducials network installed in the accelerator hall correlated nicely with the simulations. Recent observations indicate possible movement of certain fiducials beyond the thermal displacements driven by temperature gradients along the year. An assessment of the impact on the GCF and the uncertainties on the measurements on both fiducials displacements due to potential building settling effects and temperature variations in the accelerator hall is here provided.

THE INTERNATIONAL FUSION MATERIAL IRRADIATION FACILITY (IFMIF)

A fusion relevant neutron source is a pending step for the successful development of fusion energy. Safe design, construction and licensing of a nuclear fusion facility by the corresponding Nuclear Regulatory agency will demand the understanding of the materials degradation under the neutrons irradiation during the life-time of the fusion reactor. The deuterium–tritium nuclear fusion reactions in a fusion power plant will generate neutron fluxes in the order of 10^{18} m^{-2} s^{-1} with an energy of 14.1 MeV. The first wall of the reactor vessel, a complex combination of layers of different materials will be most exposed undergoing potentially >15 dpaNRT per year of operation [1]. It is indispensable that the plasma facing components can withstand the operational conditions without degradation of their mechanical and physical properties beyond defined thresholds driven, not only by nuclear safety reasons, but also by investment protection aspects. Qualifying suitable materials at equivalent irradiation conditions as in a fusion reactor is a first step that concurrently with the understanding of the materials behaviour will lead, in hand with computations techniques, to the development of new materials capable of making the operation of a nuclear fusion power plant viable.

IFMIF, the International Fusion Materials Irradiation Facility, presently in its Engineering Validation and Engineering Design Activities (EVEDA) phase under the frame of the Broader Approach Agreement between Japan and EURATOM, which entered into force on June 2007, has the mandate 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 sub-system.

IFMIF will generate a neutron flux with a broad peak at 14 MeV by Li(d,xn) nuclear reactions thanks to two parallel deuteron accelerators colliding in a liquid Li screen with a footprint of 200 mm x 50 mm. The energy of the beam (40 MeV) and the current of the parallel accelerators (2 x 125 mA) have been tuned to maximize the neutron flux (10^{18} m^{-2} s^{-1}) to get irradiation conditions comparable to those in the first wall of a fusion reactor in a volume of 0.5 l that can accommodate around 1000 small specimens [2].

The accomplished design of IFMIF plant is intimately linked with the validation activities carried out over the first 6 years of the IFMIF/EVEDA phase. It consists of five major systems: (1) the Accelerator Facility; (2) the Li Target Facility; (3) the Test Facility, (4) the Post-Irradiation and Examination (PIE) Facility, and (5) the Conventional Facility compliant with international nuclear facility regulations. The validation activities have focused on the three technological challenges: (1) the Accelerator Facility, (2) the Target Facility, and (3) the Test Facility. Three major prototypes have been designed and are either presently operating or being manufactured: (1) an accelerator prototype at Rokkasho, cloning those of IFMIF up to its first superconductive accelerating stage to be completed in June 2017 [3]; (2) a Li Test Loop (ELTL) at Oarai, integrating all elements of the IFMIF Li Target Facility, commissioned in February 2011, and (3) the High Flux Test Module with a prototype of the capsules housing the small specimens to be irradiated in the BR2 fission reactor of SCK/CEN Mol and its Helium gas cooling plant. The validation activities and its most recent status have been described elsewhere [4].

THE LINEAR IFMIF PROTOTYPE ACCELERATOR (LIPAc)

LIPAc is IFMIF's prototype accelerator that will reach a beam average power of 1.125 MW with deuterons in CW (175 MHz) at 125 mA and 9 MeV. It will validate the accelerators of IFMIF (125 mA in CW at 40 MeV) by demonstrating that the space charge issues can be overcome at 9 MeV, its lowest energy superconducting accelerator stage (the 40 MeV will be achieved in three additional SC stages at 14.5, 26 and 40). This is feasible due to the gradually smaller impact of space charge issues at growing energies, cancelling in the relativistic domain at high β beams [5]. The involved high power and beam nature entails investment protection arguments and radiation safety aspects.

LIPAc have been designed and constructed mainly in European labs (CIEMAT, CEA, INFN and SCK CEN) with participation of JAEA, is currently under installation at Rokkasho (Japan). The study of LIPAc and IFMIF accelerator's beam losses has been a matter of various publications, the most recent one is [6]; its high current demands beam losses in the order of 10^{-6} from nominal ones to meet the operation and maintenance requirements. Traditional emittance matching approach with Twiss parameters is not sufficient and beam halo matching novel system will be applied [7].

THE ALIGNMENT OF THE LIPAC

Requirements

Due to the very high intensity and power of the beam of LIPAc, beam losses must be minimized and kept below 1 W/m in order to control undesired activation and allow 'hands-on maintenance on the accelerator components. Beam dynamics MonteCarlo multi-particle calculations have been performed in order to evaluate the effects of random alignment errors of the components of the beam losses [8]. Table 1 lists the allowable tolerance for the alignment of the component with respect to the beam line to match the target requirements for beam losses.

Instrumentation and software

In order to meet the tolerance alignment requirements for LIPAc, a high precision instrument as a laser tracker is essential, following the experience in other labs for similar requirements (CERN, DESY, SLAC) [9]. A laser tracker Leica AT401 has been adopted due to its high performance. Among the others, the main characteristic of the tracker are [10,11]:

- Accurate digital nivel with an MPE levelling capability of ±1 arcsec, comparable with the digital nivels in the market;
- MPE angle accuracy of ±15 µm +6 µm/m according to B89.4.19-2006 [12];
- ±10 µm absolute distance accuracy, according to B89.4.19-2006 [12];
- Large volume capability up;
- High portability and easy connection with WIFI;

Table 1: Error distributions from the beam dynamics calculations [8].

Error Type	Error range
LEBT	
Solenoids Misalignment [x,y]	±0.2 mm
Solenoids Tilt [φ_x,φ_y]	±3.5 mrad
RFQ	
RFQ Segment Misalignment [x,y]	±0.1 mm
RFQ Voltage (first harmonic shape)	±2 %
RFQ Mean Radius	±20 μm
RFQ Vane Radius	±20 μm
MEBT	
Quadrupoles Misalignment [x,y]	±0.2 mm
Quadrupoles Tilt [φ_x,φ_y]	±10 mrad
Buncher cavities Misalignment [x,y]	±1 mm
Buncher cavities Tilt [φ_x,φ_y]	±30 mrad
BPMs Measurement Accuracy	±0.1 mm
SRF linac	
Resonators Misalignment [x,y]	±2 mm
Resonators Tilt [φ_x,φ_y]	±20 mrad
Resonators Field amplitude	±1 %
Resonators Field phase	±1 deg
Solenoids Misalignment [x,y]	±1 mm
Solenoids Tilt [φ_x,φ_y]	±10 mrad
BPMs Measurement Accuracy	±0.25 mm
HEBT	
Quadrupoles Misalignment [x,y]	±0.2 mm
Quadrupoles Tilt [φ_x,φ_y]	±15 mrad
Quadrupoles Tilt [φ_z]	±3 mrad
Dipole Misalignment [x,y]	±1 mm
Dipole Tilt [φ_x,φ_y,φ_z]	±10 mrad
BPMs Measurement Accuracy	±0.1 mm

Concerning the software, we decided to follow F4E's ITER metrology team based on their experience with SA® (Spatial Analyzer) Ultimate [13]. Among the most relevant features [14, 15, 16]:

- The capability of giving an estimation of the uncertainty via complex Montecarlo simulations through the USMN (Unified Spatial Metrology Network) algorithm;
- The use of advanced weight technique compared to traditional bundle adjustment to combine measurements for different instruments/stations to increase accuracy (e.g difference weight of the measurements as a function of the different distances to the instrument, the possibility of weighting differently, according to the characteristic of the instrument, the angle component to the distance component, etc.);
- The USMN algorithm is GUM compliant and meets the ISO standard requirements;

- The capability of simulate measurements in order to predict uncertainty and the possibility to optimize the measurement process in advance.
- The capability of USMN algorithm to evaluate the measurements performance.

Definition of the network

An update of the network in the accelerator vault was agreed in 2013 [17]. The decision was taken because of the typical masking of some fiducials during the installation of some conventional equipment (Figure 1).

Figure 1. Part of the existing fiducials were hidden by conventional equipment (cable trays).

This situation could only get worse with the planned installations in the accelerator vault. Moreover, the obtainable uncertainty resulted to be too large to match the requirements with measurements uncertainties above the target precisions. We decided to get help from the F4E's ITER metrology team according to their many years of experience on accelerator alignment and working with the most advanced technologies.

In compliance to NIST and ISO standards, a measurement is complete only when accompanied by a quantitative statement of its uncertainty in order to prove traceability of the measurement results [14, 18]. As a general good measurement rule, the uncertainty field of a measurement shall be a factor from 3 to 10 less than the tolerance, depending on the application [18]. According to ISO 14253 [19], the tolerance for the conformity of a measurement with the specifications should be reduced by the measurement uncertainty. Based on F4E's ITER metrology team, we decided to follow the ITER Metrology Handbook prepared by D. Wilson, setting a target uncertainty of 0.02 mm at 2 σ in the accelerator room to guarantee the alignment or determining their position within ±0.1 mm.

According to SA simulations performed by F4E's ITER metrology team, the existing original network was not capable to satisfy the target requirements with measurement uncertainties of 0.134 mm. In addition, all the existing fiducials were placed almost at the same height from the floor, thus not guaranteeing a good accuracy on the location of the instrument. New simulations carried out by F4E's ITER metrology team recommended that the placement of new 120 fiducials on the walls and on the floor (Figure 4) of the accelerator would allow the target uncertainty below 0.02 mm at 2σ.

This result was achieved simulating the measurement with the following parameters:

- Surveying all the visible network fiducials by 5 laser tracker stations (Figure 2 and 3). In this way, measuring common points from as much locations as possible, will increase rigidity on the network on the USMN construction and decrease point measurement uncertainty [16];
- Using 1000 samples for MonteCarlo simulations to define the uncertainty field point cloud of each measurement. According to [16], a minimum of 300 samples per each point should be used to approximate the uncertainty less than 5% of accuracy.

Figure 4 reports the representation in SA of the uncertainty field of the USMN network fiducials as result of the MonteCarlo calculations. Lower uncertainties are obtained in the middle of the assembly hall where lower alignment tolerances are required.

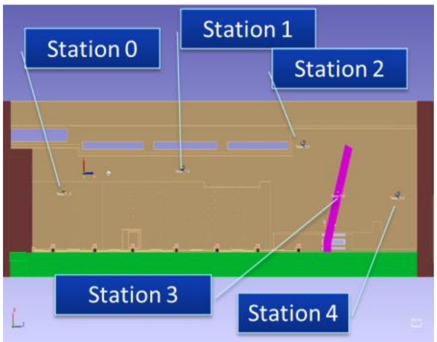

Figure 2. Position of each tracker station inside the accelerator vault

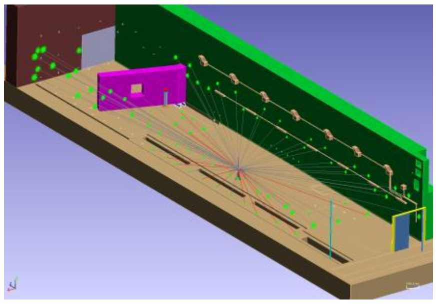

Figure 3. Typical network survey: all the visible network fiducials are measured to increase rigidity on the USMN algorithm to lower uncertainties.

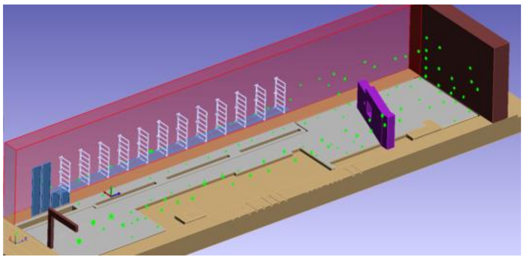

Figure 4. Representation of the uncertainty field of the fiducials after USMN MonteCarlo algorithm.

Figure 5 reports the 2σ uncertainty resulting from the USMN by measuring with 1000 samples points on the floor aligned with the beam line relocating the tracker in 4 locations. The lower points of the curves correspond to tracker stations. A target uncertainty below 0.02 mm is reached measuring at a distance below 2.5 - 3 m from the tracker.

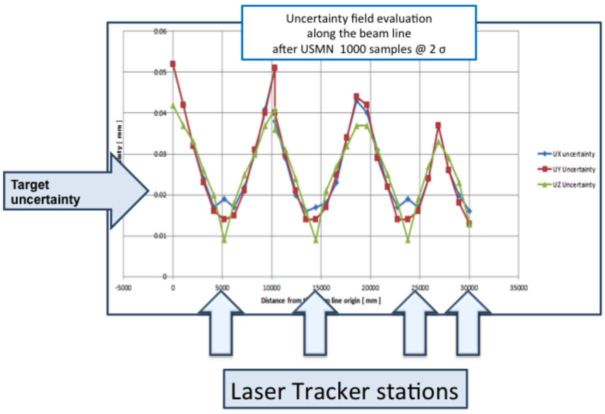

Figure 5. Result of SA simulations of measuring points on the floor aligned with the beam line from 5 tracker locations.

The network updated was accomplished in June 2013 according to the simulations: 69 ad-hoc machined supports were installed on the walls, 50 nests on the floor and a datum pillar with adjustable screws (Figure 6).

Figure 6. Floor nests (left), walls nest supports (center) and the datum pillar (right) installed in the accelerator vault.

The survey campain of the network was conducted by F4E's ITER metrology team. Before and during the survey the following actions were performed in order to increase measurements accuracy:

- Before starting each measurment of the network the tracker was warmed up for at least 3 hours as recommended by the manufacturer and as a result of a campaign test in SLAC [20];
- A field check (two face check and scale bar calibration check) was performed in the accelerator hall before starting the survey to tune up the tracker parameters as recommended from the manufacturer;
- Ckeck that any kind of vibrations and airstream induced by motor, air conditioning system, etc. are avoided;
- Perform regular drift checks of the instrument to monitor if eventual movements during measuremets occurs;
- Leica 1.5" Red Ring Reflector [21] were used and positioned with almost the same orientation to reduce systematics errors;
- Each network point was measured in two face;
- Sampling time was set to 5 s, as suggested in [20] to measure with the maximum accuracy.

All the network points has been surveyed from 5 different laser tracker positions in agreement with the simulations. All the points were merged with the USMN algortithm and the MonteCarlo uncertainty analysis was made with 1000 samples. Figure 7 shows the a comparison on the uncertainty of the simulations and the real surveys of points on the floor aligned with the beamline with the tracker positioned at about 15 m from the origin. The real uncertanty seemed to be different from the simulated one probably due to the real environment conditions. However, the uncertainty value is still acceptable for points on the floor which distance is less than 2 - 2.5 m far from the tracker.

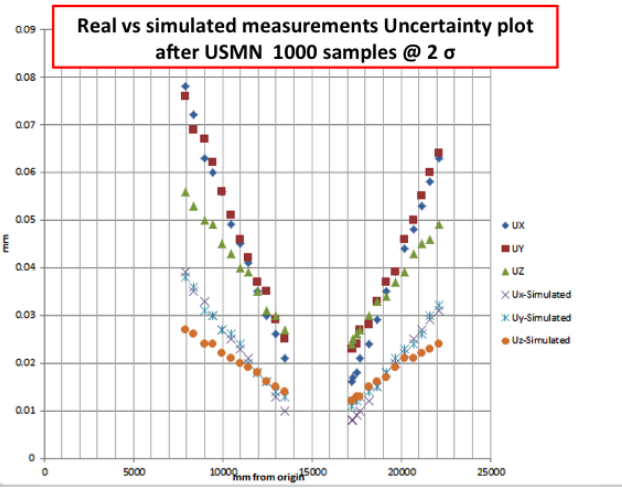

Figure 7. Comparison between the uncertainty of the simulations and the real survey on an almost straight line on the floor aligned with the beam line.

Definition of the Beam Line Frame (BLF) and the Global Coordinate Frame (GLF)

A new coordinate frame has been defined. The old reference coordinate was poorly defined: the coordinates of the points of the old network were pointing at an origin that was placed on the beam line on the floor, 1.5 m below the beam axis. The new coordinate frame was constructed in agreement with the 3D mock up, and the horizontality has been improved (Figure 8).

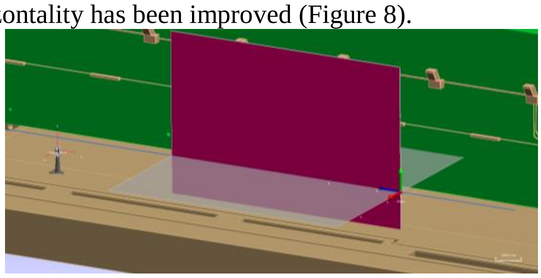

Figure 8. Definition of the beam line frame

This would simplify the assembly process, since in practice the components will be fiducialised respect the beam line. The new beam line frame was defined by:

- An origin: the origin is defined as the interface point on the beam line between the Low Energy Beam Transport and the Radio Frequency Quadrupole (RFQ), 1.5 m above the floor.
- An horizontal plane passing through the origin, which define the vertical Y axis. Instead of using a traditional approach to define it by means of a digital level, we decided to generate it using the built-in nivel of the AT401. The tracker was placed in the middle of the accelerator vault in order to average the earth curvature (0.1 mm every 40 m).
- The beam line axis Z: it is defined by best fitting the existing reference fiducials obtained on the new survey with the old coordinates. The obtained axis is then projected to the horizontal plane.

Since the BLF is not materialized, a Global Coordinate Frame (GCF) inside the vault worth being defined for possible quick check for the impact of undesired external events, like an earthquake, that might produce component misalignment. The reference system has been aligned with respect to the beam line and a permanent pillar (Figure 5) with a particular fiducial on the floor. The passage in SA from GCF and BLF is allowed by a transformation matrix.

Effect of thermal expansion of the building

Since Rokkasho's accelerator location suffers of hard winters and hot summers, we decided to study the possible impact of the thermal expansion of the building on the survey of the fiducials following the suggestions of Japanese accelerator experts.

The treatment of a thermal expansion of a building is not as trivial as it may appear due to the combination of thermal inertia and non-isotropic expansion.

SA allows the thermal compensation by only isotropic scaling all the measurements taken by an instrument [22, 23]:

- Using a thermal expansion coefficient and defining a reference temperature and a working temperature;
- Using a scaling factor;

We decided initially to establish a simple procedure, avoiding generation of complicated data and optimizing available time, considering the following assumptions:

- The most important contribution to the thermal expansion of the building is coming from the floor from X and Z directions;
- Thermal expansion along Y axis could be difficult to be measured, being comparable to the accuracy of the tracker.

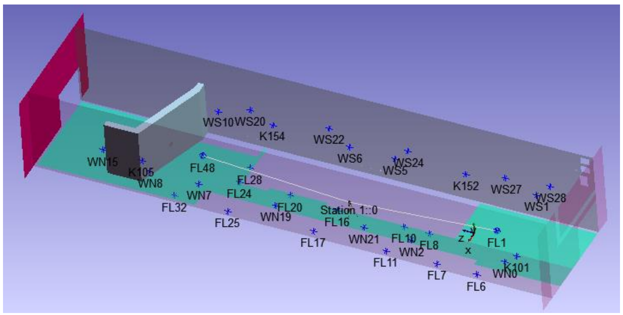

Figure 9. Layout of the two selected points to be measured periodically (white shots).

We decided to perform the following measurements periodically for a period covering at least one summer and one winter and recording all the data on a spreadsheet:

- Measure with a Fluke 568 [24] the temperature on 30 evenly spread locations on the floor, to assure the uniformity of temperature;
- Measure with the AT401 placed always in the same position the distance of two fiducials on the floor almost aligned with the beam line for a total distance over 20 m (Figure 9). In order to increase the accuracy of the measurement the tracker was positioned on the floor by the Romer base and as much aligned as possible with the line of sight of the two fiducials (Figure 10). For total angle of less than 5° the uncertainty on the measurement coming from the encoders is almost negligible [25];
- Measure the environment temperature and relative humidity in the assembly hall using the AT401 meteo station;
- Measure the LEICA invar reference scale bar and its temperature to prove traceability.

Figure 10. The tracker placed on the foor in order to increase accuracy reducing the influence of the angular encoder on the measurement.

In this way it should be possible to calculate a th ermal expansion coefficient of the building or a scaling factor to be introduced in SA and adopted for the surveys. According to the data registered up to now, we found from begin of May to September a difference of the average floor temperature of about 10±0.5 °C at 2σ. According to SA simulations this would lead to difference of measurement of about 0.2 mm in X direction and 0.05 mm in Y direction if no thermal compensation is considered. Thus the calculated scaling factor has been used for the surveys if needed to increase accuracy of the measurements.

The alignment if the injector and future components

The mechanical installation of the injector, carried out under CEA responsibility, has been finished in May 2014. The alignment of the equipment (source, Low Energy Beam Transport (LEBT) and diagnostic box) has been performed with the Taylor Hobson system. The references for the optical target on the wall and the telescope, a temporary pillar fixed on the floor were previously installed and aligned to the BLF with the AT401 (Figure 10).

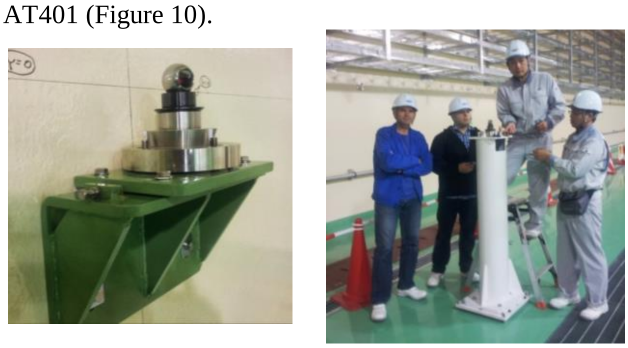

Figure 11. The references for the Taylor Hobson for the alignment of the injector: wall bracket on the wall (left) and the reference pillar (right).

After the installation, the fiducialization of the source and the LEBT was performed with the AT401 (Figure 12). The resulted uncertainty of the measurement from SA USMN calculations was kept for all fiducials below 40 μm, acceptable for a target uncertainty of 0.2 mm. This will allow the assembly within the tolerance range for the future removal and reposition of the LEBT for the RFQ assembly.

Concerning the assembly of the other components of the accelerator, each component will be delivered already fiducialized by each lab. The use of SA simulations is essential for the placements of the fiducials and to calculate the estimated uncertainty that can be obtained.

Figure 12. LEBT and source survey with the AT401 in the accelerator hall.

Update of the network

An update of the alignment network fiducials was conducted in August 2014. It was no more possible to locate the instrument using 8 - 10 fiducials close with an RMS error below 0.03 mm, thus it was not possible to keep uncertainty below 0.02 mm to assess the alignment of the components within ±0.1 mm, even with scaling the measuremens with thermal expansion.

The same procedure for the definition of the network was followed with the same instrument parameters. The only difference the station on the beam dump area was avoided since no high accuracy is required for the moment in that area, the installation of the beam dump occurring in 2017.

The new measurements have been fitted to the old measurements through the USMN algorithm in order to keep the origin as closest as possible to the existing.

Figure 13, 14, 15 and 16 report the magnitude X, Y, Z deviations of the new network respect to the old one in 2013. All the points are adjusted mainly in a symmetrical manner (thermal compensation effect) in particular for the X and Z direction. It seemed that some more deviations related with building settling effects were registered and adjusted in Y direction, especially close to the injector area. The update of the network affected little the GCF, being the beam line deviated of max 50 μm in both X and Y for a total distance of 24 m.

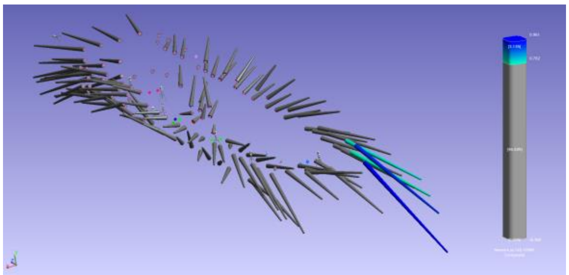

Figure 13. Magnitude deviation between the old and the new USMN network.

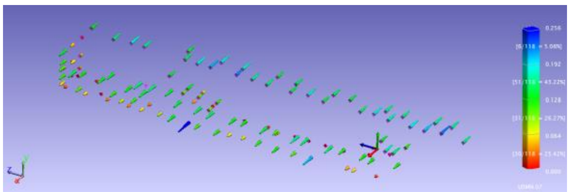

Figure 14. Deviation along X axis between the old and the new USMN network.

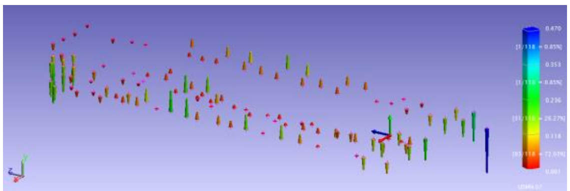

Figure 15. Deviation along Y axis between the old and the new USMN network.

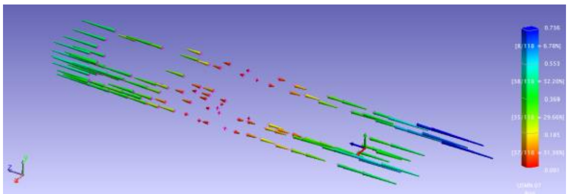

Figure 16. Deviation along Z axis between the old and the new USMN network.

CONCLUSIONS

LIPAc presents the highest perveance (the parameter that describe the beam space charge relevance [26]) of existing worldwide accelerators. Its target 9 MeV beam validates the 40 MeV of IFMIF since space charge phenomena tend to disappear at growing energies. The high current of LIPAc (125 mA in CW, matching that of IFMIF) and high inelastic cross section of deuterons drive its high alignment accuracy and precision to allow beam operation conditions and 'hands-on' maintenance strategy. Careful beam dynamics simulations carried out [6,7,8] defined the positioning requirements of individual equipment to keep beam losses within needed values (see Table 1). In turn, alignment simulations with the original survey network in the accelerator hall predicted uncertainties in the measurements above the target alignment values; this would have made unachievable the required precision. An upgrade of the survey network was undertaken in 2013 following simulations with Spatial Analyzer®, carried out by the F4E's ITER metrology team, adviced 120 new fiducials randomly placed. A survey campaign in June 2013 confirmed the validity of the simulations with uncertainties in the measurement within 30 µm, in compliance with ITER Metrology Handbook.

Potential settling effects observed in the building and impact on ΔT in Rokkasho across the year, have advised to carry out an update of the network over the summer 2014 to allow efficient alignment of the components during the on-going LIPAc installation phases, as well as a careful assessment of the uncertainties in the measurement with regular survey exercises across the year, which is presently being performed.

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