EVALUATION OF QUADRUPOLE MAGNETS MISALIGNMENT IN THE IFMIF PROTOTYPE ACCELERATOR USING THE BEAM BASED-ALIGNMENT METHOD

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Abstract

The beam commissioning of the Linear IFMIF Prototype Accelerator (LIPAc) in what is called Phase B+ configuration has started since July 2021 to confirm the performances of beam transport elements and beam diagnostic instrumentations for achieving the Radio Frequency Quadrupole (RFQ) beam operation in CW. A fine-tuning of the beam center to pass through the magnetic centers of the quadrupole magnets in the beamline was performed using a Beam-Based alignment (BBA) method. To gain confidence in the measurements, a comparison with the measurement of positions performed with a laser tracker was made. The BBA showed a good agreement of misalignment of about 0.5 mm in the horizontal direction between the RFQ exit and the magnetic axis of the first quadrupole magnet of the Medium Energy Beam Transport section (MEBT) measured by the laser tracker. We confirmed that the measurement accuracy of BBA was insufficient to assess the quadrupole magnets' misalignments in some sections of the beamline.

INTRODUCTION

The LIPAc was designed and developed to validate the accelerating of a 125 mA deuteron beam up to 9 MeV using an RFQ with a length of 9.8 m and a Superconducting Radio Frequency linac (SRF) in the CW operation for realizing the IFMIF project [1]. This activity has been promoted in a collaboration between Japan and European Union institutes. The accelerator sub-systems were designed manufactured and tested in Europe and are integrated as one accelerator system at the QST Rokkasho site.

In July 2019, we succeeded in accelerating a 125 mA deuteron beam to 5 MeV at a low duty cycle of 0.1% using the RFQ, calling this beam campaign “Phase B” [1]. In “Phase B+”, we plan to accelerate a deuteron beam to 5 MeV in the CW operation with the RFQ and also transport it to a beam dump located 15 m from the RFQ exit without unwanted particle losses to validate diagnostics performances and the beam dump commissioning toward high DC up to CW.

For the Phase B+ campaign, the beamline was extended temporarily from MEBT to High Energy Beam Transport (HEBT) sections, named as MEBT Extension Line (MEL), as shown in Fig. 1 where an SRF Linac is installed in the following Phase, and additional beam monitors were also installed along the beamline [2,3]. The components in the MEBT sections were installed in 2017 within the required tolerance of alignment of +/-0.2 mm [4 - 6]. However, we found a horizontal misalignment of 0.5 mm between the mechanical center of the RFQ exit and the magnetic axis of the first quadruple magnet in MEBT, through the laser tracker survey in 2020, whereas the other components were aligned within the requirement. We nevertheless decided not to realign the MEBT component because particle simulation with the TraceWin code [7] showed that particles

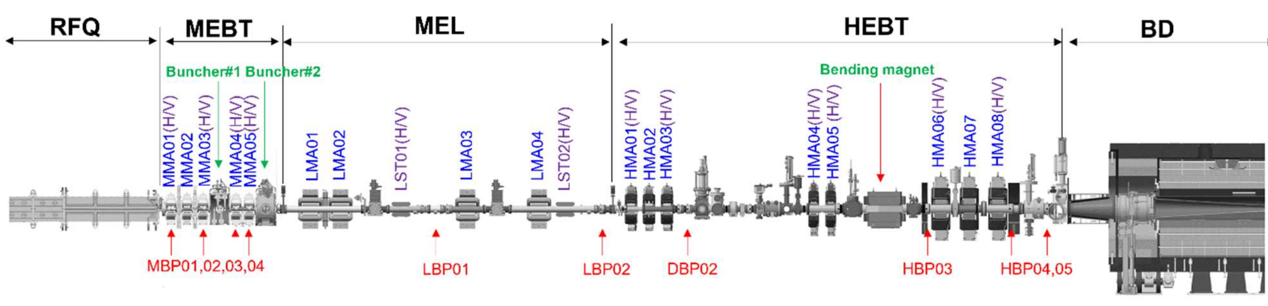

Figure 1: The Phase B+ LIPAc beamline from the exit of RFQ to the entrance of the high-power Beam Dump (BD). Reds: BPMs, blues: quadrupole magnets, purples: steering magnets, greens: bunchers and bending magnet.

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would not be lost at the low beam currents in the primary beam operation campaign.

In July 2021, we started the first stage of the Phase B+ operation. One of the major purposes of this stage was to confirm the performances of beam diagnostic instrumentations using the low-current proton and deuteron beams in preparation to the following stages targeting the nominal beam current of 125 mA in CW. Beam position monitors (BPMs) [8] are useful to confirm the misalignment between the RFQ exit and the first quadrupole magnet (quad), using a Beam-Based Alignment (BBA) method [9] with a proton beam (10 mA, 2.5 MeV, 0.1 ms pulse). The beam condition was chosen to suppress the radiation damage to the components as low as possible due to the beam hit.

A fine-tuning of the beam center to pass through the magnetic centers of the quads was also performed using the BBA method with a 5 MeV deuteron beam (20 mA, 5 MeV, 0.1 ms pulse). Moreover, from the steering kick angles and beam positions at quads obtained by the BBA, we examined whether the alignment of quads placed over a 10 m distance from the MEBT to the HEBT sections can be evaluated using a beam within several hours instead of a laser tracker-based alignment survey which for the LIPAc in the present configuration takes a few days.

THE LIPAc BEAMLINE

The LIPAc consists of an ion source that can generate a proton or a deuteron beam, a Low Energy Beam Transport (LEBT) section to guide the beam from the ion source to the next section, an RFQ with a length of 9.8 m to accelerate the beam, a MEBT section, a MEL, a HEBT section [2,3] with a bending magnet, and a Beam dump (BD).

A 50 keV/u deuteron (proton) beam generated at the ion source is accelerated up to 2.5 MeV/u in the RFQ. Then the beam matched transversely by a triplet and a doublet of quads in the MEBT section [10] is transported to the MEL section with two sets of doublets of quad magnets. In the HEBT section, the beam delivered from MEL is focused by a triplet and a doublet of quads and then is bent by a dipole magnet with a bending angle of 20 degrees to the BD.

Figure 1 shows the LIPAc beamline with the component names from the middle of the RFQ to the BD. The first triplet quad is placed close to the exit of the RFQ because the beam needs to be focused to suppress the effect by the strong space charge force.

BPMs in the MEBT section are placed at the middle positions of each quad, while BPMs in the MEL and HEBT sections are placed separately from the quads. The first and the last quads of triplets are equipped with steering magnets in the MEBT and HEBT sections, and with all the quads in doublets. In the MEL section, two steering magnets are placed separately from the quads.

BEAM POSITION MEASUREMENT WITH QUADRUPLE SCAN METHOD

A beam passing off the center of a quad is kicked by a dipole field of the quad, which causes the beam to be displaced downstream of the quad. Let us consider a case shown in Fig. 2 where the quad Q0 is scanned while Q1 and Q2 are fixed at their nominal strengths, and their centers are aligned. When the beam positions in phase space at each magnet and a BPM are (x_0, x'_0), (x_1, x'_1), (x_2, x'_2), and (x_B, x'_B), respectively, the relation between them can be written as

$$x_B = (x_2 + L_2 x_2') + L_2 k_2 x_2, \quad x'_B = k_2 x_2 + x_2', \tag{1}$$

$$x_2 = (x_1 + L_1 x_1') + L_1 k_1 x_1, \quad x'_2 = k_1 x_1 + x_1', \tag{2}$$

$$x_1 = (x_0 + L_0 x_0') + L_0 k_0 x_0, \quad x'_1 = k_0 x_0 + x_0', \tag{3}$$

where L_0, L_1, and L_2 denote distances between components and k_0, k_1 *and* k_2 denote the normalized magnetic strength of the quad, as shown in Fig. 2.

When the strength k_0 of quad Q0 is changed by dk_0, induced beam displacement dx_B at the BPM can be obtained by

$$dx_B = \left(\frac{\partial x_2}{\partial k_0} dk_0 + L_2 \frac{\partial x'_2}{\partial k_0} dk_0\right) + L_2 k_2 \frac{\partial x_2}{\partial k_0} dk_0. \tag{4}$$

From the Eqns. (2) and (3), we have

$$\frac{\partial x_2}{\partial k_0} = x_0 (L_0 + L_1 + L_1 L_0 k_1), \quad \frac{\partial x'_2}{\partial k_0} = x_0 (k_1 L_0 + 1). \tag{5}$$

By substituting Eqn. (5) into Eqn. (4), the beam displacement dx_B at a BPM for a triplet quad is written as

$$dx_B = x_0 dk_0 [(L_0 + L_1 + L_2) + (L_1 + L_2) k_1 L_0 + (L_0 + L_1 + L_1 L_0 k_1) k_2 L_2]. \tag{6}$$

Therefore, the beam position from the magnetic center of the quad is

$$x_0 = \frac{dx_B}{dk_0 [(L_0+L_1+L_2)+(L_1+L_2)k_1 L_0+(L_0+L_1+L_1 L_0 k_1)k_2 L_2]}. \tag{7}$$

Then, the error σ_{x_0} of the beam position is given by an error in dx_B/dk_0, $\sigma_{\frac{dx_B}{dk_0}}$, as follows.

$$\sigma_{x_0} = \sigma_{\frac{dx_B}{dk_0}} \frac{1}{|(L_0+L_1+L_2)+(L_1+L_2)k_1 L_0+(L_0+L_1+L_1 L_0 k_1)k_2 L_2|}. \tag{8}$$

In a doublet case, $k_2=0$ (or $k_1=0$) reduces Eqn. (8) as,

$$x_0 = \frac{dx_B}{dk_0 [(L_0+L_1+L_2)+(L_1+L_2)k_1 L_0]}, \quad \sigma_{x_0} = \sigma_{\frac{dx_B}{dk_0}} \frac{1}{|(L_0+L_1+L_2)+(L_1+L_2)k_1 L_0|}. \tag{9}$$

In a singlet magnet case, $k_1 = k_2 = 0$. Therefore, it is reduced further as,

$$x_0 = \frac{dx_B}{dk_0 [(L_0+L_1+L_2)]}, \quad \sigma_{x_0} = \sigma_{\frac{dx_B}{dk_0}} \frac{1}{|(L_0+L_1+L_2)|}. \tag{10}$$

BEAM BASED ALIGNMENT METHOD

The BBA is used to determine the optimum current of a steering magnet placed upstream of the target quad so that the beam at the downstream BPM is not displaced by a scan

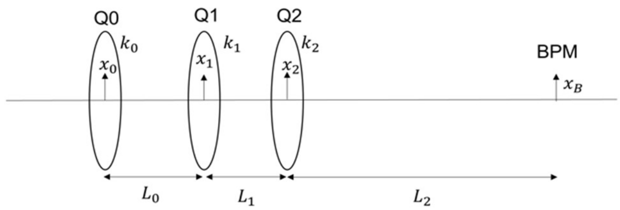

Figure 2: Special configuration of Q0 quad scan for the first one of three quads with a BPM at downstream.

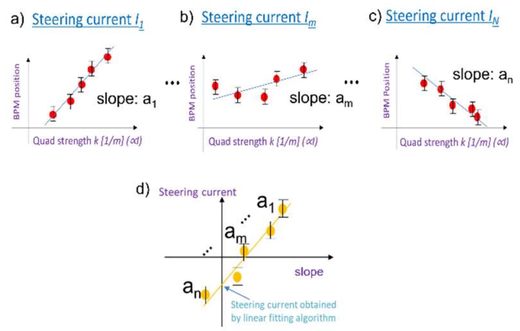

Figure 3: Conceptual plots to be measured by BBA.

of the quad. As explained in the previous section, we should determine a steering magnet current so as to be $dx_0=0$ in Eqn. (10).

We made a script to optimize steering currents via BBA for LIPAc. Below is the procedure implemented to the script:

1. Set a steering magnet current, I_1.
2. Scan the quad strength (current), k_0, and measure beam position using the BPM at each step of the quad scan, see Fig a).
3. Repeat 1 and 2 for various I_m, see Fig.3 a), b), c).
4. Fit the measured beam positions at the BPM as a function of quad strength (current) using linear fitting. Get slopes (corresponding to dx_B/dk_0's in Eqn. (10)) for each steering current.
5. Fit the steering current as a function of the slopes with linear fitting, see Fig. 3 d).
6. Set the steering current where the slope equals zero.

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MISALIGNMENT BETWEEN RFQ EXIT AND MEBT QUADS

The laser tracker-based alignment survey showed a horizontal misalignment of -0.5 mm between the exit of the RFQ and the magnetic axis of the first quad in MEBT, as mentioned before. To confirm such a misalignment, we measured the beam positions with the BPMs at the middle of MMA01 and MMA03 (the first and the third quads in MEBT, see Fig. 1), using the quad scan method with a 2.5 MeV proton beam and the BBA script. Under the assumption that centers of BPMs are well aligned, the beam position at the RFQ exit was estimated by solving transfer matrix equations between MMA01&3 and MMA01& RFQ exit.

Figure 4 shows the results of quad scans for MMA01 and MMA03. For the MMA01 scan, the beam displacements were measured with MBP02 at the condition of MMA02 OFF (see Fig. 1). For the MMA03 scan, MMA01 and 02 were set to the nominal currents, and MBP03 was used to monitor the beam displacements. The quad scans were carried out twice at different days to confirm the reproducibility of the beam positions measured using the BPMs. From Eq. (10), beam positions can be obtained with slopes and distances between the target quad and BPM. Table 1 shows the beam positions and divergences at the RFQ exit, MMA01, and MMA03. The beam angles x', y' required to estimate the beam position at the RFQ exit were computed with the beam positions and the transfer matrix between MMA01 and MMA03. As a result, it is found that the beam passed through at around -1 mm and 0.1 mm in the horizontal and vertical planes, respectively, from their magnetic centers.

Figure 5 shows the positions of the RFQ exit, MMA01, and MMA03 to compare the misalignments measured with the proton beam and the laser tracker system. As a baseline (zero positions in the vertical axes) to compare them, we chose a line passing through the magnetic centers of MMA01 and MMA03. Here we assume that the beam comes out of the center of the RFQ exit. In the horizontal plane in Fig.4, the RFQ exit is found to be at around -0.5 mm with respect to the magnetic centers of the two quads. For the vertical plane, they are found aligned well. The misalignments in both planes measured with the proton beam are consistent with those surveyed with the laser tracker. Hence, we could confirm a 0.5 mm horizontal

Table 1: Beam Positions and Divergences at the RFQ Exit MMA01 and MMA03

Name	Date	$(x \pm \sigma_x, x' \pm \sigma_{x'})$	$(y \pm \sigma_y, y' \pm \sigma_{y'})$
RFQ exit	Thu.	(−0.47± 0.08, −3.06± 0.22)	(0.15± 0.12, 0.22± 0.48)
	Fri.	(−0.59± 0.06, −2.98± 0.21)	(0.04± 0.13, 0.05± 0.56)
MMA01	Thu.	(−1.01± 0.07, −3.06± 0.22)	(0.19± 0.08, 0.22± 0.48)
	Fri.	(−1.09± 0.05, −2.98± 0.21)	(0.05± 0.09, 0.05± 0.56)
MMA03	Thu.	(−1.13± 0.15, −2.16± 0.64)	(0.24± 0.10, −1.43± 0.65)
	Fri.	(−0.97± 0.15, −1.57± 0.56)	(0.06± 0.12, −0.37± 1.41)

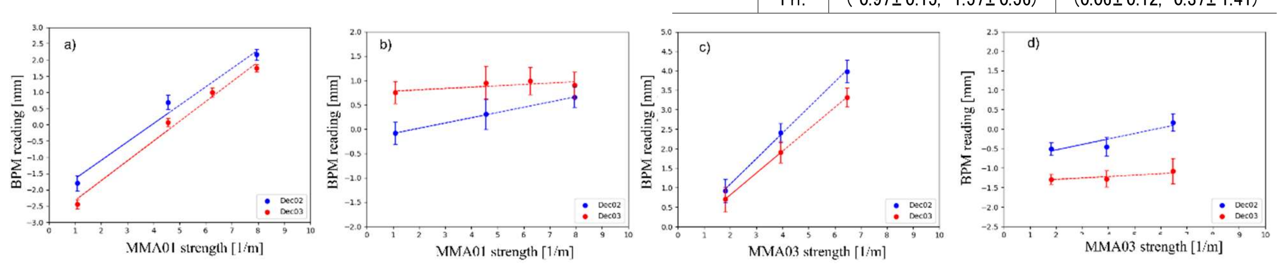

Figure 4: The plots of quad scans for MMA01(left two plots) and MMA03 (right two plots). a) and c): the horizontal plane and b) and d): the vertical plane. Blue and red colors show the results carried out at different days.

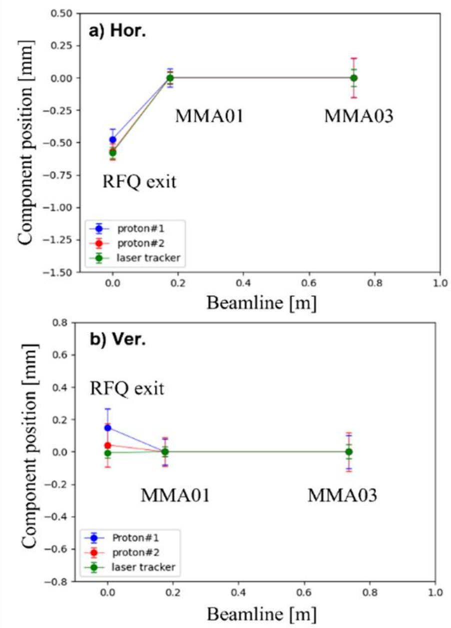

Figure 5: The positions of the RFQ exit, MMA01, and MMA03. a) and b) are the horizontal and vertical positions, respectively. Zero positions in the vertical axes is a line passing through the magnetic centers of MMA01 and MMA03.

misalignment between the RFQ exit and MEBT quads exit and also the validity of the BBA procedure implemented to the script.

BEAM-BASED ALIGNMENT OF BEAMS TO QUADS

We carried out the BBA with a 5 MeV deuteron beam for the last quads of the doublet and triplet magnets and then scanned all the quads except for MMA01&02 to identify the beam center positions with respect to the magnetic centers. Figure 6 shows the beam center positions at each quad obtained by the BBA. The vertical axis in Fig. 6 represents the horizontal or vertical distance from the magnetic center of each quad. Note that the beam positions plotted in Fig. 6 were calculated with Eqns. (7)-(9) since the other quads were set to the nominal currents while the BBA for a target quad was performed. From Fig.6, it is concluded that the beam could pass through within +/-0.2 mm from the magnetic centers of all quads except for MMA04 and HMA07 after the BBA.

The vertical beam position at MMA04 in Fig.6 is far from the magnetic center, and the error is also larger than the other ones. The reasons are that the distance between MMA04 and the used BPM (MBP04) was close (L=0.23 m) and also the measured signal of MBP04 was not stable [11,12] both of which are seen in Eqn. (10) to contribute to a large σ_{x_0}. One of the simple methods to reduce the error is to choose a BPM long away from the quad such as LBP01 downstream of MBP04 (see Fig. 1).

In the HEBT section, the horizontal beam center position at HMA07 is far from the magnetic center. This is simply

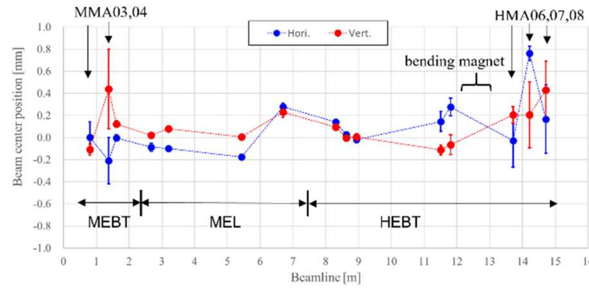

Figure 6: Beam center positions at each quadruple magnet after the BBA.

because we did not tune the bending magnet due to the limited beam commissioning time, and the horizontal steering magnet between the bending magnet and HMA07 was not strong enough to adjust the beam. The vertical errors at the last triplet quads of HEBT are larger than the other ones. One of the reasons is that HEBT BPMs were unstable due to a hardware problem similarly to the MEBT one mentioned above [11,12]. Currently, efforts are being made for a better stability in BPM signals [11,12].

Since we confirmed that the beam was transported to the magnetic centers of most quads within +/-0.2 mm by the BBA, we will calibrate each BPM by setting the electrical offset so that the electrical center of the BPM matches with the magnetic center of the nearest quad in the next beam campaign.

QUAD POSITIONS MEASURED BY BBA AND LASER TRACKER SYSTEM

Figure 7 shows relative quad positions from the baseline from the MMA03 to the last quad HMA05 measured by BBA and the laser tracker system. The last triplet magnets in the HEBT section are excluded since the coordinate system are different before and after the bending magnet. In order to compare quad positions measured by the two methods, we chose a line passing through the magnetic centers of MMA05 and LMA01 as a baseline. Here, the beam divergences of MMA05 and LMA01 were calculated by solving a transfer matrix equation using the beam positions of MMA05 and LMA01, and then the relative quad positions were evaluated using each local beam position at each quad and steering kick angle obtained by BBA. The errors were also estimated with

$$\sigma_{x\{i+1\}} = \sqrt{\{m_{11}^2\sigma_{xi}^2 + m_{12}^2\sigma_{x'i}^2\}}, \qquad (11)$$

where m_{11} and m_{12} represent elements of a transfer matrix between target quads.

Regarding the beam-based horizontal quad positions in Fig. 7, we can see, unlike the laser-tracker-based ones, large misalignments with respect to the baseline ($x=0$) from the last MEL quad to the last HEBT quad. We confirmed after the beam campaign that the alignment surveyed by the laser tracker system has a reproducibility. Possible causes for the discrepancy beyond the assumed errors can be some systematic errors in the present beam-

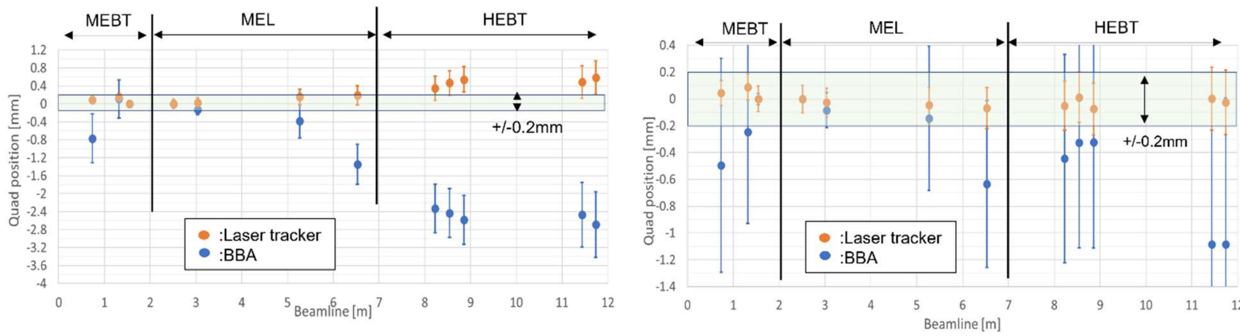

Figure 7: Comparisons of quad positions measured with a 5 MeV beam and the laser tracker system. The left and right plots show the horizontal and the vertical planes. Note that the vertical scales are different in the two plots. Blue and orange colors stand for the results measured by the BBA method and laser tracker system, respectively.

based measurements. However, the cause of the large discrepancy has not been identified yet, and is planned to be studied further in the next beam campaign.

The vertical quad positions have large errors, thus it is difficult to compare the quad positions measured by the two methods. The large errors are due to the accumulated errors owing to large transfer matrix elements m_{12} in Eqn. (11). Therefore, it is difficult to evaluate alignments of quads over a 10 m distance from the MEBT to HEBT using a beam. As a next step, we will compare quad positions by each section or a short section such as between MEBT and the first half of MEL and the latter half of MEL and quads in the HEBT.

CONCLUSIONS

The magnetic misalignment between the RFQ exit and the first MEBT quad measured with the BBA method using a 10 mA, 2.5 MeV proton beam was consistent with the geometrical misalignment measured with the laser tracker system. We could also confirm the validity of the BBA script via the misalignment evaluation.

The BBA method was performed using a 20 mA, 5 MeV deuteron beam, and the beam could be transported through all the centers of quads, within +/-0.2 mm, except one after the bending magnet, for which optimization of the bending magnet current is required. We will calibrate the BPMs by the BBA in the next beam campaign.

To investigate the possibility of an alignment survey using a beam over a 10 m distance, we tried to compare quad center positions measured by the BBA and the results of the laser tracker survey. As a conclusion, it was difficult to evaluate the alignments of quads using a beam over a 10 distance since the accumulated errors were too large. We conclude that the application of this method should be limited to a shorter distance unless errors in beam positions in the individual quads are made smaller in the future.

DISCLAIMER

This work was undertaken under the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan. The views and opinions expressed herein do not necessarily state or reflect those of the Parties to this Agreement.

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