ALIGNMENT OF CAVITIES AND MAGNETS AT J-PARC LINAC

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Abstract

An alignment of J-PARC linac has been completed. A fine alignment is performed in installing the accelerating section. A detailed survey is conducted after the initial alignment. Subsequently, a limited number of components are realigned putting emphasis on realizing a smooth alignment rather than attaining an idealized straight alignment. During the installation, a floor elevation is carefully addressed to accommodate a possible elevation change to a smooth alignment.

INTRODUCTION

It has been widely accepted that a precise alignment is a key to achieve high beam quality and highly stable operation increasingly demanded in recent particle accelerators. As colliding machines and the latest light sources are the most demanding, it holds true for high intensity machines also. In recent high intensity hadron accelerators, even a small fractional beam loss induces serious radio-activation, which undermines the mentenancibility of the accelerator components. One of the causes of the beam loss is considered to be the orbit distortion and resulting emittance growth due to misalignment of the accelerator elements. Therefore, special care should be taken to the design of the alignment from an early stage of the component design. Particularly, the beam loss budget should be carefully addressed in determining the error tolerances for an alignment procedure for high intensity machines. J-PARC (Japan Proton Accelerator Research Complex) accelerator is one of the latest high intensity proton accelerators, which consists of a linac, 3-GeV Rapid Cycling Synchrotron (RCS), and 50-GeV Main Ring (MR) [1]. The beam power of 1 MW is aimed to utilize it for wide-ranging applications from life science to neutrino physics.

As shown in Fig. 1, the linac consists of an Ion Source (IS), Radio-Frequency Quadruple linac (RFQ, 3m), Drift Tube Linac (DTL, 30 m), and Separate-type DTL (SDTL, 90 m). RFQ and DTL are connected with a short beam transport line called MEBT (Medium Energy Beam Transport, 3 m). The beam is accelerated to 181 MeV by the linac, and led to RCS through a beam transport line called L3BT (Linac-to-3-GeV RCS Beam Transport). L3BT is composed of a straight section (170 m), 90-degree arc section, collimator section, 17.6-degree arc section, and injection section.

The alignment plan for a large-scale accelerator should address wide-ranging issues, which includes component specifications regarding the alignment accuracy, installation and precise alignment procedures, schedule planning, and monitoring of floor elevation. Furthermore, it is often extended to cover geological assessment for site selection and civil engineering design of the accelerator tunnel. Among these issues, we focus in this paper on the installation and precise alignment procedure for J-PARC linac, which has been performed from Jun. 2005 to Sept. 2006. In advance of the installation, DTQ's (Drift Tube Quadrupole magnets) are installed into DTL tanks offline. As the alignment of DTQ involves a rather complicated procedure of peculiarity, we do not elaborate into it in this paper. Instead, we focus on the procedure of installing and precisely align the accelerator components into the linac tunnel.

The accelerator components are often aligned roughly in the installation, and then a fine alignment is performed after its completion. However, we have performed a fine alignment in installing the components because of a peculiar reason as discussed later. J-PARC accelerator is situated beside the ocean, and built on sandy soil with abundant groundwater. In these unique circumstances, the floor elevation might be substantially influenced by the groundwater level. As the alignment period extends over 16 months, the possible floor elevation change during the alignment period should be carefully addressed. The alignment strategy is elaborated to accommodate the possible elevation change.

In this paper, we describe the alignment procedures employed for J-PARC linac, and present the results of the initial alignment.

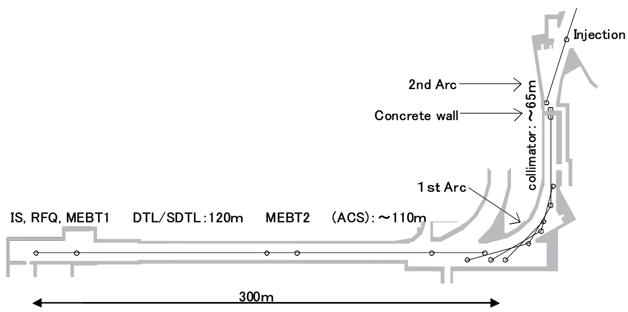

Fig. 1: Layout of the J-PARC linac tunnel. Distribution of the floor monuments for the coarse network is also shown with open circles.

ALIGNMENT STRATEGY

In designing the alignment procedure for J-PARC linac, special care is to be taken to the DTL alignment. The DTL section consists of three DTL tanks (DTL1, DTL2, and DTL3 from the upstream side), and each tank has the length of about 10 m. A DTL tank is composed of three units, to which we refer as "unit tanks", of the length of about 3 m. These unit tanks are connected with a vacuum flange, and we slide them along a liner guide in connecting to form a DTL tank. To ensure the proper connection, these linear guides should be aligned parallel with an accuracy of ±0.05 mm for the full sliding range (typically 150 mm) in advance of the unit tank installation. As the DTL tank is rather long and has two vacuum connections in the middle of the tank, it is difficult to make a position adjustment after combining the unit tanks. Under these conditions, we have determined to perform a precise alignment in installing the DTL tanks.

A distinctive feature of our DTL is the electro-magnetic DTQ's employed to attain flexible operational tunability [1, 2, 3]. Heavy wiring and piping for DTQ's are involved in the DTL installation, and it imposes a severe restriction for the management of the installation schedule. To accommodate an appropriate installation period for DTL, we have determined to start the installation from the upstream end. Then, the installation of the accelerating cavities is performed tank by tank from RFQ, conducting a precise alignment at the same time.

In adopting the alignment procedure, the following three issues should be carefully addressed. At first, the alignment period of the accelerating section is prolonged and extends over 7 months. Then, the possible elevation change during the alignment period should be properly dealt with. Secondly, we should carefully circumvent the error accumulation towards the downstream end. Finally, the alignment procedure should be compatible with the possible offline maintenance of accelerating cavities. In the initial alignment, there is no tank on the downstream side of the tank under adjustment. Although it can significantly simplify the alignment procedure, we should prepare a procedure to reproduce the cavity position after assumed offline maintenance. This position reproduction should be performed without removing downstream components.

To accommodate the elevation change during the alignment period, we put emphasis on realizing a smooth alignment rather than attaining an idealized straight alignment. We suppose that a smooth alignment can easily be realized as long as the elevation change is sufficiently smooth. In addition, we have performed frequent level surveys in order to detect an unexpected abrupt change of the floor elevation.

To avoid an error accumulation in the horizontal direction, we have utilized a long-distance measurement with a high precision total station (Leica TDA5005). At first, we have set up a coarse network over the whole linac tunnel in advance of the cavity installation. Then, the reference points, or auxiliary references, for the cavity installation are set up with the reference to the coarse network. In setting up the reference points, the error accumulation is carefully avoided with an effective use of a long-distance measurement.

The initial alignment of accelerating cavities is conducted with an alignment telescope set on the beam line [4]. This configuration is possible only without the downstream cavities. To be compatible with potential offline maintenance, each component is equipped with an off-axis reference base accessible from the pathway side of the accelerator tunnel. A laser tracker (Leica LT600) is assumed for the off-axis measurement, and the initial alignment results are transferred to the off-axis references [5].

After the completion of the installation and precise alignment, a detailed survey is conducted with a laser tracker. In this survey, a minute network is set up with the offline references. A minimum position adjustment is conducted for SDTL to attain reasonably smooth alignment. Meanwhile, no realignment has been performed for DTL tolerating a larger deflection at the exit of DTL. To correct the deflection, a set of steering magnet with a larger deflection angle has been prepared at the exit of DTL.

The alignment goal for quadruple magnets and RF cavities are set to +/-0.1 mm and +/-0.3 mm, respectively [6]. The smooth deflection of 0.05 mm / 10 m is also tolerated. The same alignment goal is assumed for the downstream beam transport line also.

The alignment of the beam transport line is straightforward. We have adopted a usual two-step approach with an initial rough installation and final precise alignment after the completion of the installation. The alignment of the beam transport line is conducted in parallel with the cavity installation. A laser tracker is employed both in the installation and the final alignment. The coarse network and auxiliary references mentioned above are utilized in the installation of the beam transport line also. An important issue regarding the alignment of the beam transport line is the absorption of the relative alignment error between linac and RCS. Although the relative position between linac and RCS has been measured in advance of the installation, it is unavoidable to have a certain inconsistency in these positions after the installation and alignment period. The inconsistency is absorbed by adjusting the length of two specific drift spaces (one in each of the collimator line and injection line), and slightly modifying the bending angle of the second arc section. A vertical difference is to be corrected by introducing a slight vertical deflection at the exit of the first arc section or the second arc section.

ALIGNMENT PROCEDURE

Preparation

According to the alignment strategy, adequate alignment references are prepared for each accelerator component. As mentioned above, accelerating section should be compatible with the alignment with both an alignment telescope and a laser tracker. The initial alignment is carried out with an alignment telescope using an on-axis reference. Meanwhile, a realignment and a monitoring survey assume a measurement with a laser tracker using an off-axis reference. Then, the components in the accelerating section has both on-axis and off-axis references.

The on-axis reference is basically an optical target holder, whereas the off-axis reference is a reference base compatible with a variety of targets. The reference base is standardized among J-PARC facilities, and basically a stainless steel plate with a reference hole of the standardized geometry (See Fig. 2). Various targets are attached on the reference hole with adopters, and the compatible targets include a CCR (Corner Cube Reflector) for a laser tracker, an optical target for an alignment telescope, a staff for a y level [6]. Precise position reproducibility of the adopter is ensured by adopting a high precision fitting attachment (Hirai High-touch set).

Each accelerator component has at least two reference bases basically. A quadrupole doublet is assembled at a factory, and the three-dimensional measurement is conducted being assembled. Accordingly, each quadrupole magnet in the SDTL section is equipped with one reference base (See Fig. 2), and a quadrupole doublet is aligned online as one component.

Before installing the components into the accelerator tunnel, the following preparations have been performed offline. At first, DT's (Drift Tubes) and DTQ's are aligned in a DTL tank and SDTL tank. Secondly, quadrupole doublets and triples are assembled. Finally, the position of the off-axis reference is adjusted with respective to the on-axis reference. The relative position between these two references of the quadrupole magnet is ensured by a precise three-dimensional measurement at faculty assembling. That for DTL and SDTL is adjusted using a template (See Fig. 2).

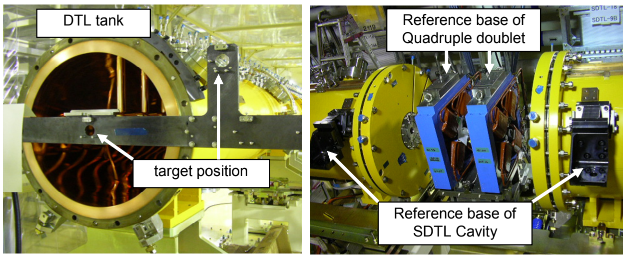

Fig. 2: Photographs of alignment references for DTL and SDTL. Left: Off-axis reference bases for SDTL tanks and a quadrupole doublet in the SDTL section. The same off-axis reference base is adopted for a DTL tank also. Right: A template for a DTL tank, which serves both as the on-axis reference and the reference to adjust the off-axis reference.

Initial alignment

A survey over a network covering the whole J-PARC facility has been performed periodically [7]. We have three access holes to transfer the results of the survey into the linac tunnel. Based on the transferred coordinates, a coarse network is set up for the installation, which covers the whole linac tunnel. Floor monuments are placed at the reference points for this network [8]. The distribution of the reference points for this network is shown in Fig 1. In setting up the coarse network, a high-precision total station is utilized. The accelerator components are aligned along the line formed by the network.

From our experience, a practical measurement range for an alignment telescope is around 10 m to ensure the accuracy of half the transverse tolerance (50 μm). Meanwhile, the distance between the reference points for the coarse network exceeds 100 m. Then, we need to set up an auxiliary reference for every 10 m. The axis of the alignment telescope is aligned to the coarse network utilizing the auxiliary reference points. The auxiliary references are aligned to the coarse network with a long-distance measurement with a high-precision total station

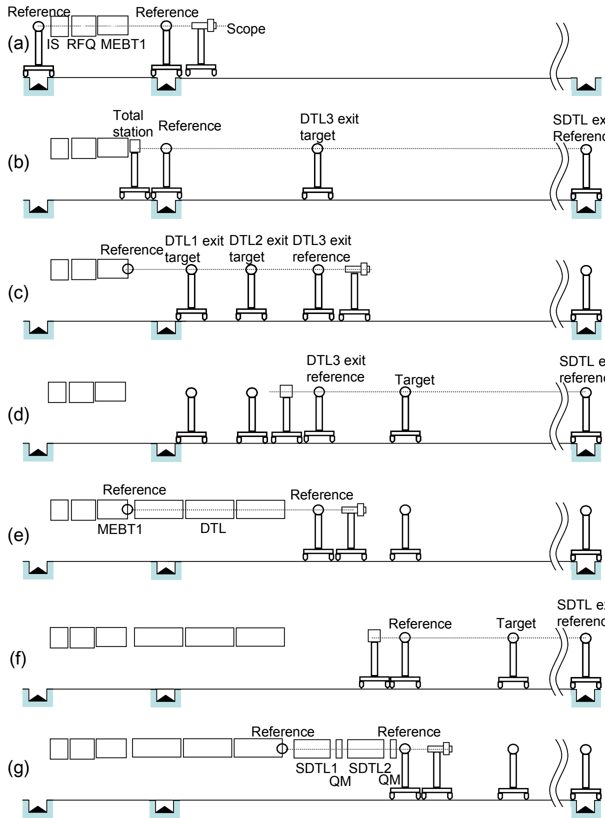

Fig. 3: Schematics of the initial alignment procedure for DTL and SDTL tanks. The ion source, RFQ, and MEBT are aligned using the upstream two references in (a). Then, an auxiliary reference is set up at the exit of DTL3 with a long-distance measurement in (b). Using this auxiliary reference, two other references are set up at the exit of DTL1 and DTL2, respectively, in (c). Here, the last quadrupole magnet in MEBT is utilized as a temporal reference. These references are utilized for the alignment of DTL tanks. Before installing DTL3, another reference is set up in (d), which is used for the alignment of upstream SDTL tanks. In installing the DTL tanks, auxiliary references are removed one by one from upstream side in (e). Then, before installing upstream SDTL tanks, another reference is set up using a total station in (f), which is used for the alignment of the following a few SDTL tanks. In the alignment of the upstream SDTL tanks, the on-axis target at the DTL3 exit is utilized as a temporal reference in (g). Repeating analogous procedures, the SDTL tanks are aligned from the upstream end.

The procedure of the initial alignment is summarized in Fig. 3. At first, we set up references on three reference points for the coarse network at the ion source, the MEBT exit, and the SDTL exit. The references are set up on the floor monuments, and their height is adjusted with a digital level (Leica DNA03). In setting up an auxiliary reference, the reference at the SDTL exit is taken as a reference with a long-distance measurement so that we can avoid the error accumulation towards the downstream end.

Precise survey and realignment

After the completion of the initial alignment, a periodical survey should be performed to ensure an appropriate alignment. The alignment scheme for the initial alignment is not suitable for this purpose, because it supposes an on-axis measurement. Therefore, a minute network for a laser tracker measurement has been established to this end. This network is also utilized to reproduce the cavity location after possible offline maintenance as mentioned above. The network is set up with off-axis references on the components and wall monuments placed with the interval of 5 m. In the measurement, the measurement range of the laser tracker is limited to about 10 m to attain the required accuracy. Then, the laser tracker is moved with a step of 5 m to cover the entire linac.

The error ellipsoid estimated for this survey network [9] is shown in Fig. 4. As seen in this figure, larger errors of up to 0.9 mm and 1 mm are expected at the upstream end and the downstream end of the linac, respectively. This inaccuracy arises from the elongated shape of the linac tunnel. However, the expected error suggests a possible gradual bent due to an accumulation of measurement errors. The accuracy in the range of about 20 m is expected to be better than 0.1 mm. Therefore, the displacement in a localized area is expected to be in the tolerable range.

After completing the initial alignment, a detailed survey with the fine network is performed. Then, a minimum realignment is conducted in the SDTL section. In this realignment, a smooth curve is determined to best fit the measured results. Then, a limited number of components are realigned to reduce the deviation around the curve.

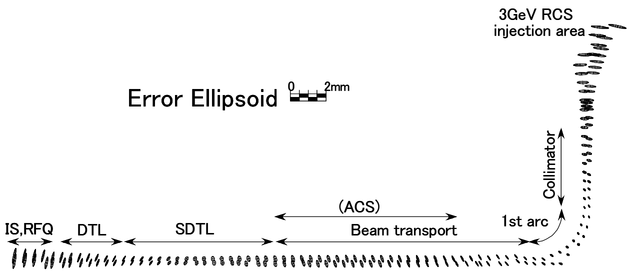

Fig. 4. The error ellipsoid for the precise survey network set up in J-PARC linac.

ALIGNMENT RESULTS

After completing the initial alignment, a detailed survey with the minute network has been performed. The results of the precise survey in the straight section are shown in Figs. 5 and 6. Figure 5 shows the measured horizontal positions, and Fig. 6 shows the vertical position. In these figures, dots show the measured position of the element center. The horizontal axis is taken as the distance along the beam line from the ion source. The height measurement is performed taking the earth curvature into consideration. Data for the components from 120 m to 140 m are missing due to a delay in manufacturing.

In Fig. 5, it is seen that the horizontal position of the component is mostly on a smooth curve. However, its curvature exceeds our expectation, and the total bent reaches 3 mm at both ends of linac. This bent is larger than the survey error predicted from the error ellipsoid shown in Fig. 4. The components are aligned along the reference for the coarse network, and the position accuracy of the references is expected to be better than 1.7 mm [10]. Accordingly, we suppose that a certain portion of this curvature is, at least, attributable to a building deformation during the installation and the error of the coarse survey.

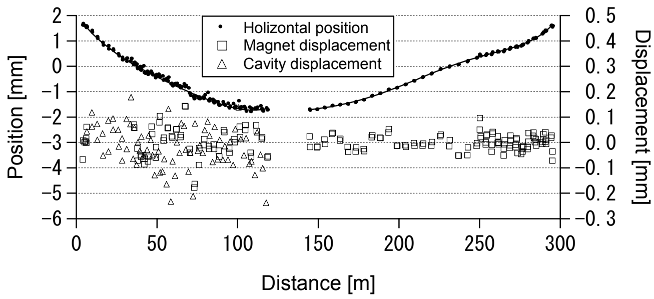

Fig. 5: The results of a precise survey for the horizontal direction (before realignment). The measured horizontal position of each element is shown with a dot, and a polynomial fit to it is shown with a solid line. The displacement from the fitted curve is shown with a square for a magnet and a triangle for an accelerating cavity..

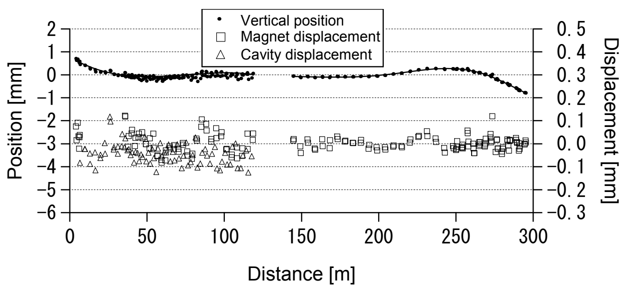

Fig. 6: The results of a precise survey for the vertical direction (before realignment). The measured vertical position of each element is shown with a dot, and a polynomial fit to it is shown with a solid line. The displacement from the fitted curve is shown with a square for a magnet and a triangle for an accelerating cavity.

In the vertical direction, components located from 30 m to 250 m are mostly aligned on a straight line as seen in Fig. 6. Discrepancy from the straight line is seen in the upstream end and the downstream portion. The bent in the downstream portion can be attributed to the floor settlement during the installation. Figure 7 shows the level variation of the tunnel floor monitored during the installation. The level survey has been performed every one month for the entire linac tunnel. Only sampled data is shown in this figure. In the level survey, the level monuments distributed over the linac tunnel are measured by a digital level. The level monument at the upstream end is taken as the height reference in Fig. 7. In this figure, the horizontal axis is taken as the distance from the ion source, and the first arc section starts at around 285 m. In Fig. 7, a settlement is observed in the area downstream from the first arc section. Due to this settlement, the floor level is bent towards the RCS injection point and the settlement reaches 2 mm at the downstream end. While a floor level variation of about ±0.25 mm is seen in the straight section, no monotonous settlement has been observed. Although we have performed detailed surveys for the accelerating section more frequently (every two weeks), no clear correlation is identified between the floor motion and environmental parameters such as the groundwater level. No abrupt change is observed in the frequent surveys. Although the amount of the variation is not negligible, its effect on the alignment is sufficiently small as seen in Fig. 6. The cause of the deflection at the DTL exit is still open, but the deflection angle is as small as 0.01 mrad.

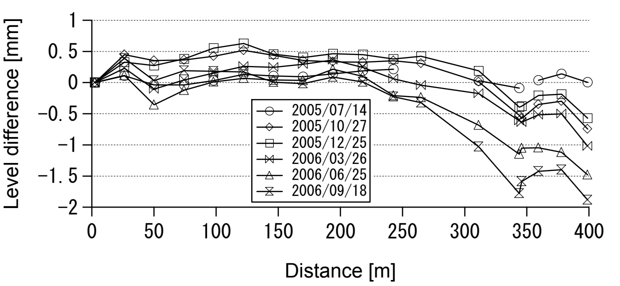

Fig. 7: The floor elevation along the beam direction. Six curves are shown for a series of six level surveys. The measured date is annotated in the figure for each curve

After the detailed survey, the realignment has been performed for the SDTL section. In this realignment, we intend to align components along a smooth curve tolerating a deviation from the idealized straight line. The curve is determined to attain sufficient smoothness minimizing the amount of the realignment. The target curves are obtained with sixth-order polynomial fit to the measured data, and they are shown in Figs. 5 and 6 with solid lines. We have used the positions of quadrupole magnets in the fitting, because the tolerances for SDTL cavities are sufficiently larger than those for magnets. Then, the displacement of each component from the target curve is shown in Figs. 5 and 6 with a square or triangle marker. Based on this data, we have selected components to be realigned. The thresholds for selecting these components are set to 0.07 mm for quadrupole magnets and 0.2 mm for SDTL cavities so as to achieve the alignment goal. In determining the thresholds, a certain margin for the measurement error is taken into consideration. The components selected with this threshold include half of quadruple doublets in the SDTL section, three SDTL cavities, and one quadruple doublet in the beam transport section. After conducting the realignment of these components with a laser tracker, the components are aligned to the target curve with the displacements shown in Fig. 8. As seen in Fig. 8, the residual misalignment is sufficiently in the tolerable range. Although a significant number of quadrupole doublets are realigned, the amount of the readjustment is rather small and typically less than 0.1 mm. Consequently, the adoption of a smooth curve significantly reduces the workload for the realignment.

In the alignment of the beam transport line, an inconsistency between the linac coordinate and the RCS coordinate is absorbed by introducing slight adjustments. The lengths of two specific drift spaces in the collimator section and the injection are adjusted. The amount of the adjustment is 4.5 mm and 4.0 mm for the collimator and injection sections, respectively. The deflection angle of a bending magnet in the second arc is slightly modified by 0.0015 deg (0.026 mrad). The difference in the vertical direction is corrected by introducing a slight deflection angle of 0.056 mrad at the exit of the first arc section.

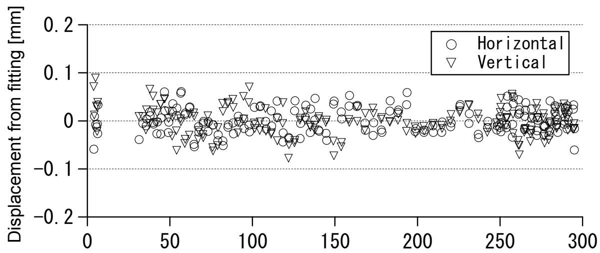

Fig. 8: The results of a precise survey after realignment. The vertical axis is the displacement from the target curves shown in Figs. 5 and 6. The horizontal displacement is shown with a circle, and vertical with a triangle.

After the realignment, it is important to ensure that the obtained alignment is properly maintained. To this end, we continue the periodical level survey to monitor the floor settlement. Figure 9 shows the trend of the floor elevation in the downstream section. The horizontal axis is the measured date, and the vertical axis is the floor elevation change since the completion of the linac tunnel in February 2005. Six curves are shown for six different level monuments. It can be confirmed in this figure that the monotonous settlement is nearly ceased in the linac tunnel. After the commencement of the beam experiment, continuous monitoring of the floor elevation is introduced with a hydrostatic leveling system [11]. According to the measurement, no peculiar floor movement has been observed so far.

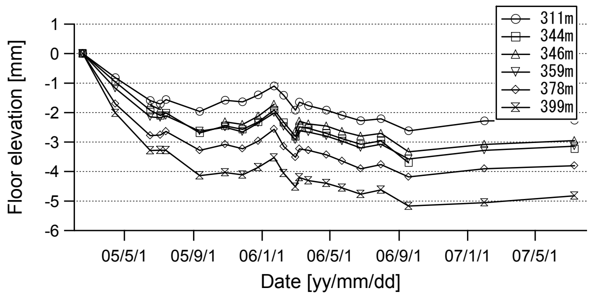

Fig. 9: The trend of floor elevation change for six monuments in the downstream section. The vertical axis is the elevation change since the building completion in February 2005.

SUMMARY

The alignment of J-PARC linac has been conducted from Jun. 2005 to Sept. 2006. In this alignment, the emphasis is put on achieving sufficient smoothness instead of pursuing an idealized straight alignment. The precise alignment of the accelerating section is performed with an alignment telescope while installing the accelerator components. The result of the precise alignment is transferred to the off-axis reference to enable a precise survey with a laser tracker. Realignment is performed in the SDTL section following a laser tracker survey. In this realignment, the components are aligned to a smooth curve instead of a straight line. In spite of the floor elevation settling during the alignment period, sufficiently smooth alignment has be achieved with an excellent accuracy.

In J-PARC linac, beam commissioning has been started since November 2006 [12, 13]. When the beam was injected into DTL1 for the first time, it was required to transport a lower energy beam of 19.7 MeV to a beam dump located some 300 m downstream. After a coarse adjustment of the RF phase and amplitude, nearly complete beam transmission was easily established without using steering magnet. This successful beam transport proves the validity of the alignment strategy and the accurateness of the alignment procedure.

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REFERENCES

[1] Y. Yamazaki (eds), “Accelerator Technical Design Report for J-PARC” JAERI-Tech 2003-044; KEK-Report 2002-13.

[2] K. Yoshino, E. Takasaki, F, Naito, T. Kato, Y. Yamazaki, K. Tajiri, T. Kawasumi, Y. Imoto, and Z. Kabeya, Proc. of 10th International Linac Conference, Monterey, California, p.569,(2000).

[3] E. Takasaki, F. Naito, H. Tanaka, K. Yoshino, T. Ito, H. Ino, Z. Kabeya, S. Kakizaki, and T. Kawasumi, Proc. of LINAC 2004, Lübeck, Germany, p. 468, (2004).

[4] H. Asano, T. Ito, T. Morishita, Y. Yamazaki, Z. Kabeya, S. Kakizaki, S. Fujie, K. Suzuki, T. Kato, F. Naito, E. Takasaki, and H. Tanaka, Proc. of 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA, p.743, (2007).

[5] T. Morishita, H. Asano, T. Ito, A. Ueno, and K. Hasegawa, F. Naito, E. Takasaki, H. Tanaka, K. Yoshino, and M. Ikegami, Proc. of 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA, p.1523, (2007).

[6] M. Ikegami, C. Kubota, F. Naito, E. Takasaki, H. Tanaka, K. Yoshino, H. Ao, T. Itou, K. Hasegawa, T. Morishita, N. Nakamura, A. Ueno, Proc. of LINAC2004. , August 2004, p474.

[7] K. Mishima and N. Tani, “Geodetic Survey Work of High Intensity Proton Accelerator Facility”, Proc. of IWAA2004, CERN, Geneva, 4-7 October 2004.

[8] T. Morishita, H. Ao, T. Ito, A. Ueno, K. Hasegawa, M. Ikegami, C. Kubota, F. Naito, E. Takasaki, H. Tanaka, K. Yoshino, Proc. of 2005 Particle Accelerator Conference, Knoxville, Tennessee, USA, p. 2851, (2005).

[9] T. Morishita, H. Asano, A. Ueno, K. Hasegawa, and M. Ikegami, Proc. of 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA, p.1520, (2007).

[10] K. Mishima, private communication.

[11] T. Morishita and M. Ikegami, “Slow ground motion monitoring system for J-PARC linac”, submitted for publication.

[12] K. Hasegawa, Proc. of 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA,p.2619 (2007).

[13] M. Ikegami and A. Ueno, “Commissioning Experience and Plans for J-PARC Linac”, Proc. of 18th ICANS, China,(2007), to be published.