# STUDY ON THE REALIGNMENT PLAN FOR J-PARC LINAC AFTER THE TOHOKU EARTHQUAKE IN JAPAN

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*Abstract*

A 9.0-magnitude earthquake struck eastern Japan on March 11, 2011, and it gave rise to damages to the buildings of the J-PARC facilities. In particular, the earthquake caused a deformation of the J-PARC linac tunnel resulting an alignment error of several tens of millimeters in both horizontal and vertical directions. It also caused some misalignment of the drift tubes in the drift tube linacs. To restore the beam operation, we should establish a reasonable realignment plan for J-PARC linac taking various constraints into account and possibly tolerating some residual misalignment. In this paper, we show a study on the realignment plan for J-PARC linac including evaluation of the effect of residual misalignment with particle simulations.

## INTRODUCTION

We had a 9.0-magnitude earthquake on March 11, 2011 off the Pacific coast of Tohoku region in Japan. While the epicenter is about 270 km far from the J-PARC [1] site, we still had a series of severe tremors which gave rise to significant damages to J-PARC facilities [2]. Especially, it caused deformation of linac tunnel of several tens of millimeters in both horizontal and vertical directions. It necessitated us to conduct urgent realignment to restore the beam operation. In this paper, we discuss on the realignment strategy after presenting the observed misalignment and results for particle simulation with excessive misalignment.

Before discussing the misalignment caused by the earthquake, we briefly review the layout and relevant design specifications of J-PARC linac. As shown in Fig. 1, J-PARC linac consists of a 50-keV negative hydrogen ion source, a 3-MeV RFQ (Radio Frequency Quadrupole linac), a 50-MeV DTL (Drift Tube Linac), and a 181-MeV SDTL (Separate-type DTL) followed by a beam transport line to the succeeding 3-GeV RCS (Rapid Cycling Synchrotron). The beam transport line consists of a straight section after SDTL, a 90-degree arc section (or the first arc), another straight section (or the collimator section), a 17.6-degree arc section (or the second arc), and the injection section. You will find the scale of the linac in Fig. 1. The tunnel length for the linac straight is 330 m.

The DTL section consists of 3 DTL tanks each of which is about 9 m long. Each DTL tank consists of 3 unit tanks connect by flanges. DTL has 143 DT's (Drift Tubes) in total. Each DT is embedded with a DTQ (Drift Tube Quadrupole) to provide the transverse focusing. As the DTQ is electro-magnetic, we have heavy power supply cabling and cooling-water piping for DTQ's.

The SDTL section consists of 30 SDTL tanks. An SDTL tank is shorter than a DTL tank, and has the length from 1.5 m to 2.6 m. Each SDTL tank has four DT's, but no DTQ is embedded. Instead, we have external quadrupole magnets in the inter-tank spacing to provide transverse focusing.

Each DT in both DTL and SDTL is supported by a vertical stem, and assumed to be susceptible to a tremor to some extent. Then, we have been worried about their possible large misalignment due to the earthquake. Especially, misalignment of DT's for DTQ is assumed to have more significant effect to the beam dynamics because of embedded DTQ's.

DTL is subject to two different stages of realignment. One is the realignment of unit tanks, and the other is the alignment of DT's inside a unit tank. Small amount of position adjustment of a unit tank can be performed without disconnecting the unit-tank flanges. However, if you assume position adjustment of, say, 1 mm or larger, you need to disconnect the unit tanks. It also involves disconnection of heavy cabling and piping for DTQ's. Meanwhile, we need to move the unit tank to an off-line working area to realign DT's in a unit tank. Then, it is required to demount almost all DT's from the unit tank to conduct DT alignment over again. Naturally, we also need to disconnect the unit tanks and cabling and piping for DTQ's. These procedure would be extraordinarily time-consuming. It is estimated that the unit tank realignment with flange disconnection would take 2.5 months and the realignment of DT's would take 6 months at least [3].

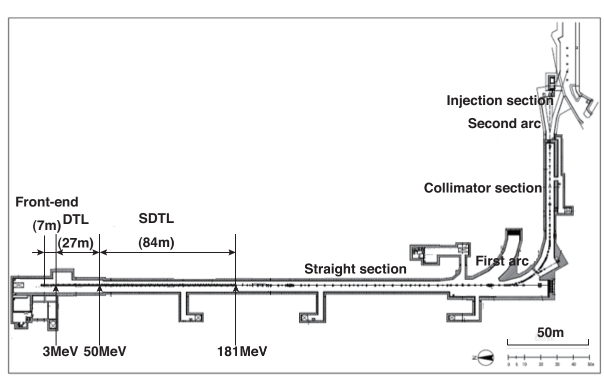


Figure 1: Scaled layout of J-PARC linac.

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Similarly, the realignment of SDTL has two stages, while they would be much more straightforward. One is the realignment of SDTL tanks and external quadrupole magnets, and the other is the realignment of drift tubes in a SDTL tank. The former is a usual alignment of accelerator components where we assume to use a laser tracker and a digital level. We also need to move the SDTL tank to an off-line working area for the latter. However, the number of DT's in a tank is much fewer, and the tolerance for the DT misalignment is assumed to be larger by a factor of several without embedded DTQ.

## MISALIGNMENT CAUSED BY THE EARTHQUAKE

### *Floor Deformation for Linac Tunnel*

Since the earthquake, we performed survey for the linac tunnel regularly [4]. Figure 2 shows data obtained at one of the surveys. In J-PARC linac, each RF cavity or quadrupole magnet has one or more references for alignment. In this figure, the elevation of the reference for each element is plotted in the vertical axis with that of the upstream end of DTL1 (or the first DTL tank) taken as the origin. (More strictly, the offset between the reference and the design beam axis is subtracted.) Then, the length along the beam line is plotted in the horizontal axis. The data is plotted up to the end of the collimator section.

It is readily seen in this figure that we had the differential settlement of around 45 mm with a sharp bend in the SDTL section. Meanwhile, the hight difference between the front-end and the end of the collimator section is several millimeters. The DTL section is leaning forward by about 0.9 mrad. Then, if we assume to put it back to a horizontal level, we need to lift up the third DTL tank by more than 20 mm involving disconnection of unit tanks as discussed above.

While the data is not shown in this paper, we also had similar deformation in the horizontal direction. The beam line has a sharp bend in the SDTL section with the maximum horizontal shift of 25 mm. Longitudinally, the tunnel length is elongated by 10 mm for the linac straight. More details will be found in the reference [4] for the tunnel deformation.

### *Drift Tube Misalignment*

Our cavity group has performed an emergent survey of DT alignment for DTL and SDTL tanks with an alignment telescope [5]. As the measurement has been conducted without moving tanks from there online position, the measurement accuracy is expected to be limited. In the survey, no obvious misalignment of DT's has been found for SDTL tanks and the last two DTL tanks. Meanwhile, some misalignment is observed in DTL1. The image analysis of photographs taken with the telescope indicated that a few of the DT's in DTL1 have misalignment of as large as 0.25 mm horizontally. However, later and more detailed measurements with an optical target showed that the misalignment is about ±0.1 mm in the both horizontal and vertical directions. The above observation suggests that the DT's in downstream tanks has smaller misalignment.

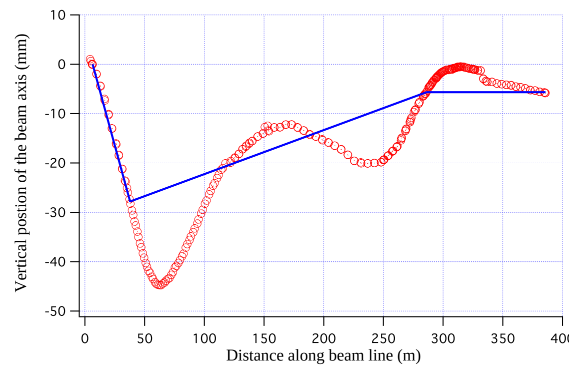


Figure 2: Elevation of linac components after the earthquake (red circles). The proposed design orbit for the realignment is also shown (blue line).

## PARTICLE SIMULATIONS

In parallel with the measurement of misalignment, we have performed particle simulations with larger misalignment than usual [6]. In the simulation, we focus on the DTL section because we found visible misalignment of DT's as discussed above. The DTL has the minimum aperture radius of 6.5 mm in the upstream portion of DTL1, and we don't have a steering magnet in the DTL section. As shown in Figs. 3 and 4, particle simulation reveals that larger misalignment of DTQ results in beam losses rather than an increase of emittance at the exit of the DTL section. It should be noted that the beam loss is mostly localized at the narrow section in the low energy part of DTL1. A decline of the transmission efficiency is not significant with the misalignment of ±0.1 mm. However, it becomes significant with the misalignment of ±0.2 mm and the transmission efficiency goes down to below 50 % in some cases. The simulation also indicates that the transmission efficiency could be restored to above 80 % with careful tuning of steering magnets just before the DTL injection as shown in Fig. 4. It is also found that we need to increase the capacity of steering magnet to cope with the DTQ misalignment of ±0.2 mm level. In conclusion, the tolerable limit for the DTQ misalignment is expected to be around ±0.2 mm considering the present peculiar situation where the soonest recovery of the beam operation is strongly requested after the earthquake. It should be noted that we here assumes the capacity increase of steering magnets as a temporary expedient. It would also be adequate to add that we have tried to simulate the effect of measured DT misalignment for DTL1, and found no significant decline in the transmission efficiency.

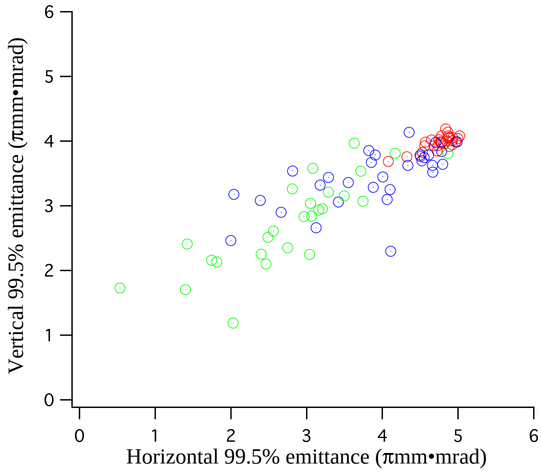


Figure 3: The simulated horizontal and vertical emittance at the DTL3 exit. Red, blue, and green circles, respectively, denote the results with the DTQ alignment error of $\pm 0.1$ mm, $\pm 0.2$ mm, and $\pm 0.3$ mm.

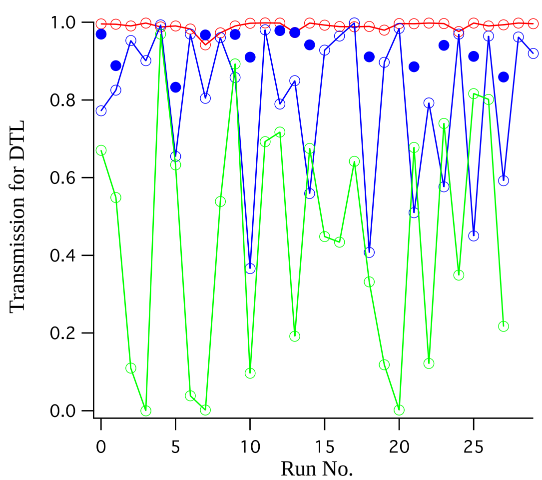


Figure 4: The simulated transmission efficiency. Red, blue, and green open circles, respectively, denote the results with the DTQ alignment error of $\pm 0.1$ mm, $\pm 0.2$ mm, and $\pm 0.3$ mm. The blue filled circles show improvement of the transmission efficiency by beam steering for some cases with $\pm 0.2$ mm DTQ misalignment.

## REALIGNMENT STRATEGY

In laying down the plan for the realignment of J-PARC linac, we naturally put emphasis on realizing the soonest recovery of the beam operation.

At first, we have concluded that the observed DT misalignment would not be critical to resume beam operation, judging from the results of the initial survey for the DT alignment and particle simulations. Then, we proposed to omit realignment of DT's for DTL and SDTL.

Secondly, we have concluded that the realignment of DTL to a horizontal level is too time-consuming requiring disconnection of the unit tanks as discussed above. We proposed to realign the DTL with the inclination angle of around -0.9 mrad to minimize the amount of position adjustment. Then, we can realign the DTL without disconnecting the unit tanks, power supply cabling, and cooling water piping.

Thirdly, the alignment of DTL with the inclination angle requires deflection of the design beam orbit at some point downstream. We proposed to deflect the design orbit at the SDTL injection by +1.0 mrad and deflect it again at the injection of the first arc section by -0.1 mrad. The remaining gap in relative position between linac and the RCS injection point is assumed to be smoothly absorbed in the beam transport line after the first arc. The assumed design orbit is shown in Fig. 2. The accelerator components are assumed to be aligned to this axis with a laser tracker and a digital level. This choice of deflecting points would require no modification of accelerator stands. We also assume similar but smaller deflections in the horizontal direction with the same deflecting points.

Finally, we proposed to absorb the longitudinal elongation in the linac tunnel adjusting the length of beam transport line just after the SDTL exit.

## SUMMARY

We had a 9.0-magnitude earthquake on March 11, 2011 in the eastern part of Japan, which caused a severe deformation of J-PARC linac tunnel and necessitated us to conduct urgent realignment. We proposed a realignment strategy for the linac putting emphasis on the soonest recovery of beam operation and basing on the findings in the emergent survey of DT alignment and particle simulation on the effect of large DT misalignment. The proposed strategy has been accepted by the J-PARC group, and the actual realignment is presently underway aiming at the resumption of beam operation in December 2011.

## ACKNOWLEDGMENT

We gratefully acknowledge the essential input from and discussions with our cavity group members, especially, Drs. T. Ito, F. Naito, and H. Ao. We also acknowledge the valuable discussions with Drs. H. Oguri, N. Ouchi, and K. Hasegawa.

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