DEVELOPMENT OF A LASER-BASED ALIGNMENT SYSTEM FOR THE J-PARC LINAC

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1. INTRODUCTION

A high-intensity proton accelerator facility named Japan Proton Accelerator Research Complex, or J-PARC, has been proposed as a joint project between KEK (High Energy Accelerator Research Organization) and JAERI (Japan Atomic Energy Research Institute), and the construction of its first phase has been approved by the government [1]. The construction of the linac part has recently been started at JAERI Tokai-campus. Figure 1 shows the layout of the J-PARC linac, which consists of a 50-keV IS (Ion Source), a 3-MeV RFQ (Radio Frequency Quadrupole linac), a 50-MeV DTL (Drift Tube Linac), a 190-MeV SDTL (Separate-type DTL), and a 400-MeV ACS (Annular Coupled Structure linac). The output beam of the linac is led to a 3-GeV RCS (Rapid Cycling Synchrotron) by a beam transport line named L3BT. In high-intensity proton accelerators, suppressing excess beam loss is essentially important to avoid serious radiation problems. To lower the beam loss along the linac, an accurate alignment of accelerator components, especially quadrupole magnets, is indispensable. An accurate alignment is also important to avoid beam quality deterioration, such as emittance growth. It should be noted here that it is necessary not only to perform an accurate alignment initially but also to maintain the alignment accuracy for a long period of time. To preserve the alignment accuracy, we need to continuously watch the long-term ground (floor level) motion, and re-alignment should be performed easily. To meet these requirements, we have been developing a laser-based alignment system for the linac part. The total length of the linac is about 280 m, including the straight section of the following beam transport line. The goal accuracy of this alignment system is ± 50 μm transversely. In this paper, the outline of the alignment system is presented together with some preliminary results of the feasibility tests performed with a 50 m test beam line.

2. LASER-BASED ALIGNMENT SYSTEM

The laser-based alignment system is designed based on the KEK-PF linac alignment system [2]. A conceptual drawing of the alignment system is shown in Fig. 2. A light source is located at the upstream end of the linac. As a light source, we adopt a continuous-wave DPSS (Diode-Pumped Solid State) laser with a wavelength of 532 nm (Coherent Compass532-20). This green laser has an advantage over a usual 633 nm He-Ne laser because it has a lower diffraction limit, which enables us to keep the beam spot size smaller after a long propagation length. The

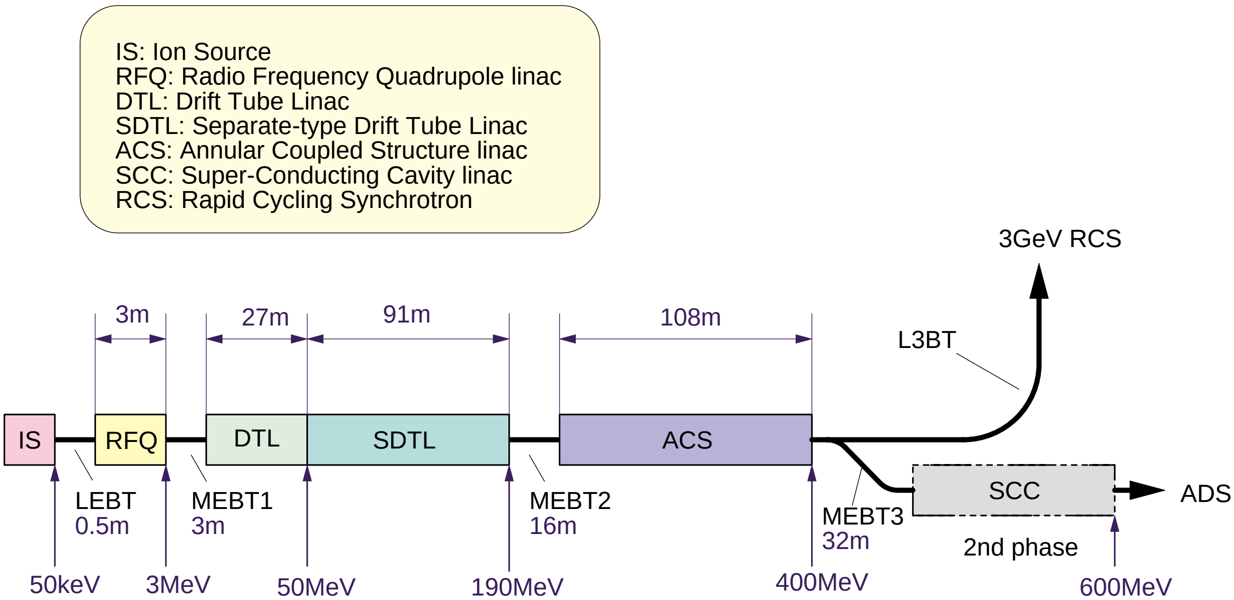


Fig. 1 Schematic layout of the J-PARC linac.

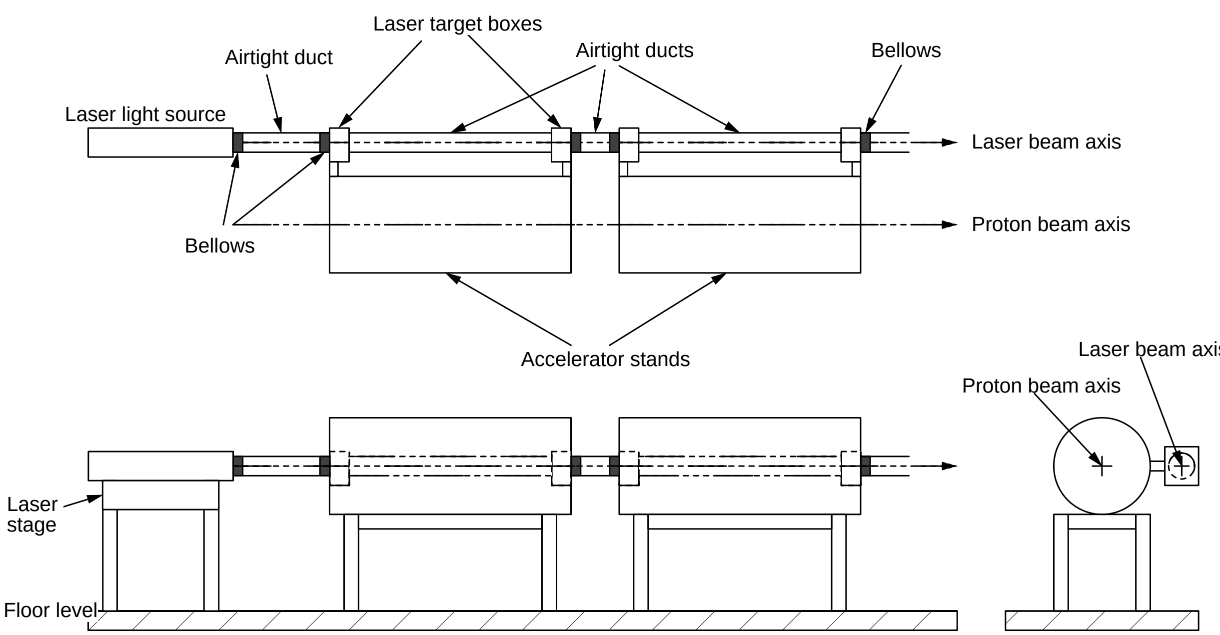


Fig. 2 Conceptual view of the laser-based alignment system.

Table 1. Main characteristics of the laser source.

Type	diode-pumped solid state
Wavelength	532 nm
Beam power	20 mW, continuous-wave
Mode	TEM00
Beam pointing stability	< 7.5 μrad/deg
Beam diameter ($1/e^2$)	0.7 mm
Beam divergence angle (full)	< 1.3 mrad
Polarization	linear

main characteristics of this light source are summarized in Table 1. An optical system is placed on a laser stage to make a parallel beam, and we have no other optical component downstream. The laser beam axis is set 700 mm horizontally away from the proton beam axis, and surrounded by an airtight duct to ease the sway by air turbulence. The inner diameter of the airtight duct is 80 mm. While a vacuum-tight duct is adopted in the KEK-PF linac alignment system, we plan to adopt an airtight duct for easy handling and manufacturing. A feasibility study of the alignment with the laser path in the atmosphere is now underway, using a 50 m test beam line as described later.

The J-PARC linac consists of accelerator components, such as rf cavities, quadrupole magnets, beam monitors, etc. Generally, several kinds of accelerator components are placed on an accelerator stand. The relative alignment among these components is performed with the usual optical alignment method using an alignment telescope. Then, accelerator stands are aligned using the laser beam as a reference line. Each accelerator stand has two laser targets at the upstream end and the downstream end. For the laser target, we use quadrant silicon photo-diodes with a diameter of 30 mm. This diameter is larger than the expected diameter of the light spot after propagation length of 280 m. This wide active area increases the resolution of the position measurement. Figure 3 shows a drawing of the laser target. The laser target consists of a quadrant photo-diode and a base plate on which the photo-diode is placed with a position accuracy of ±10 μm. By processing the photo-diode output signals, we find the position of the light spot with respect to the center of a quadrant detector. The output signal of a laser target is led to an A/D converter after a shunt resister and a low-pass filter unit, and it is processed on a computer. The horizontal displacement Δ_H can be calculated as

$$\Delta_H = \frac{(V_{UR} + V_{LR}) - (V_{UL} + V_{LL})}{V_{UR} + V_{LR} + V_{UL} + V_{LL}},$$

where we denote the output voltage from the upper-right segment of the diode as V_{UR}, the upper-left segment V_{UL}, the lower-right segment V_{LR}, and the lower-left segment V_{LL}. The vertical displacement Δ_V can be calculated in a similar way as

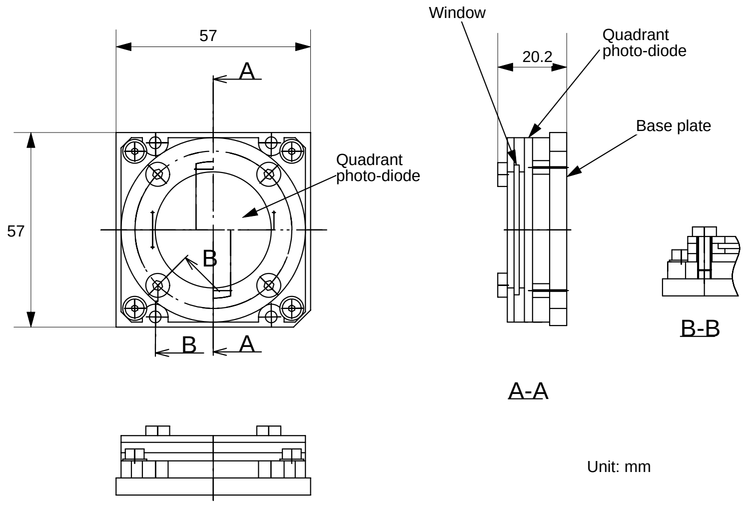


Fig. 3 Drawing of the laser target.

$$\Delta_V = \frac{(V_{UR} + V_{UL}) - (V_{LR} + V_{LL})}{V_{UR} + V_{LR} + V_{UL} + V_{LL}}.$$

The processed outputs Δ_H and Δ_V are dimensionless and supposed to be proportional to the distance between the laser-target center and the laser-beam center.

The signal-processing unit, which consists of a shunt register, a low-pass filter unit, and an A/D converter, is placed at the klystron gallery on the ground level while the accelerator components are installed in an underground accelerator tunnel, which is about 13 m lower from the ground level. Thus, the cable length between the laser target and the signal processing unit is estimated to be around 40 m.

Each laser target is installed in a box we refer to as a "laser target box". The laser target box has a driving mechanism to turn the laser target away from the laser axis. This feature is essential to enable downstream measurements, because laser targets are supposed to be attached to each accelerator stand. In Fig. 4, we show a drawing of the laser target box. The laser target is moved by rotating an inner cylinder on which a laser target is placed. Accurate position repeatability before and after rotation is required. A target box has been manufactured by way of trial, and a position reproduction of less than ±5 μm has been achieved. An optical target can be mounted on a target box as a substitute for a laser target. We plan to use optical targets to verify the system and to make a rough alignment preceding a fine one. The box is attached to an accelerator stand by an arm. As an example, Fig. 5 shows the case where the laser target box is attached to a DTL tank. The laser target position is adjusted using templates as a reference before we install the tank into the accelerator tunnel. Once the target position is adjusted, we can lock the position

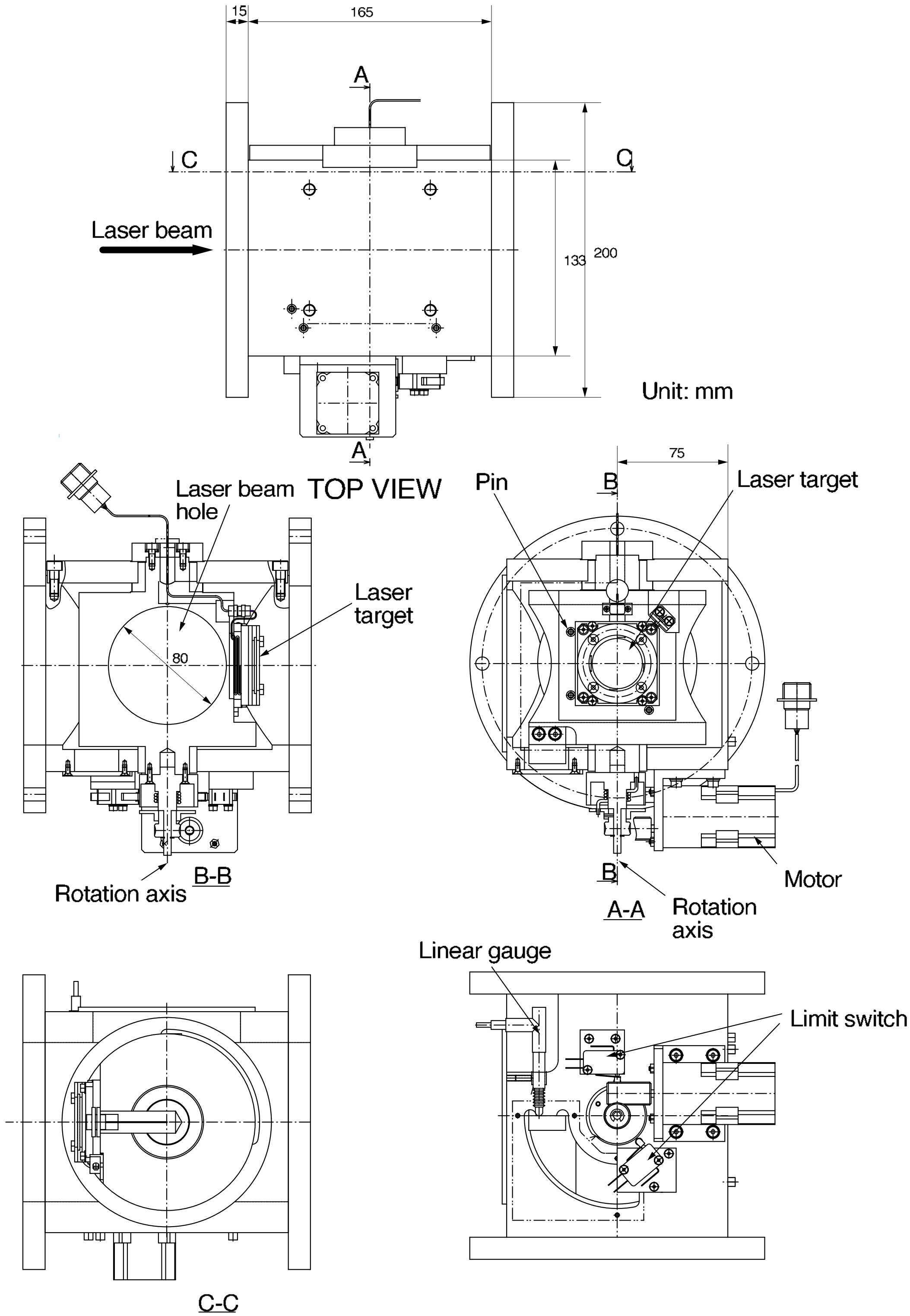


Fig. 4 Drawing of the laser target box.

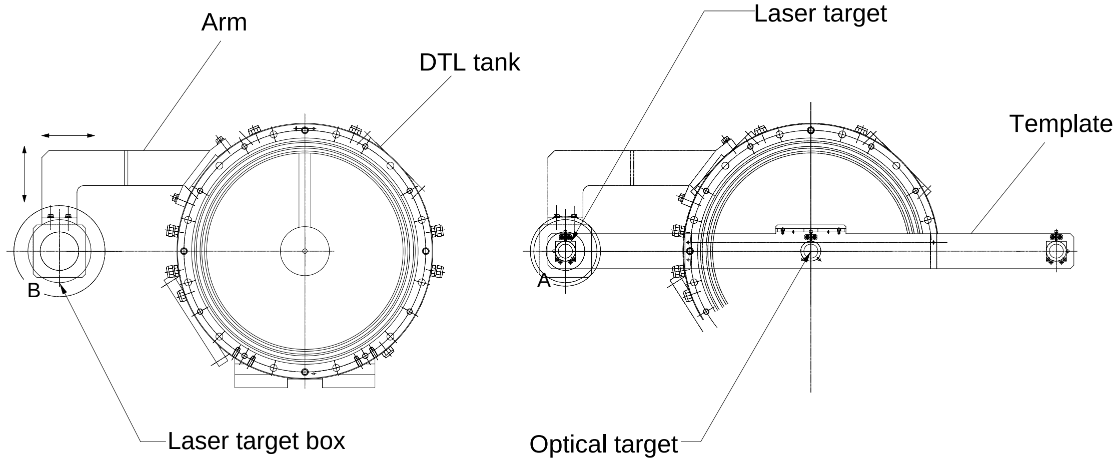


Fig. 5 Attachment of a laser target box to a DTL tank.

of the laser target box with respect to the tank. The template is a steel bar on which we can mount an optical target and a laser target. These targets are removable with accurate mounting position repeatability. The specification for the position repeatability is less than ±20 μm. An optical target is mounted on the proton beam axis, and a laser target is mounted on the laser beam axis, which is 700 mm away from the proton beam axis. Using two laser targets mounted on two templates attached to the upstream and downstream ends of a DTL tank, we set the reference laser axis for the position adjustment of laser target boxes. The optical target mounted on the proton beam axis is used for a relative alignment between a tank and the drift tubes. The specification for the machining accuracy of the template is ±20 μm. The attachment of laser targets to other parts, such as SDTL and ACS, is performed in a similar way. The rotation of an accelerator stand around the laser beam axis is avoided by using a level.

In principle, we leave the laser targets attached during beam operation, which enables us to watch the ground motion for a long period of time. However, the laser target can be easily put on and taken off with accurate mounting position repeatability. This feature is required because radiation damage of photo-diodes may be significant in some part of the linac. The specification for the position reproduction is less than ±20 μm. Radiation resistance of the laser target is an urgent investigation item.

After a long period of beam operation, it is necessary to perform re-alignment due to ground motion. As the floor on which the laser stage is placed also moves, the light direction also changes after a long period of time. Then, to enable re-alignment, the stage for the light source should have a mechanism to adjust the light direction to the designated one. The procedure to determine the light direction in the re-alignment should be decided considering the connection to downstream alignment procedures. The connection scheme between the alignment system for the

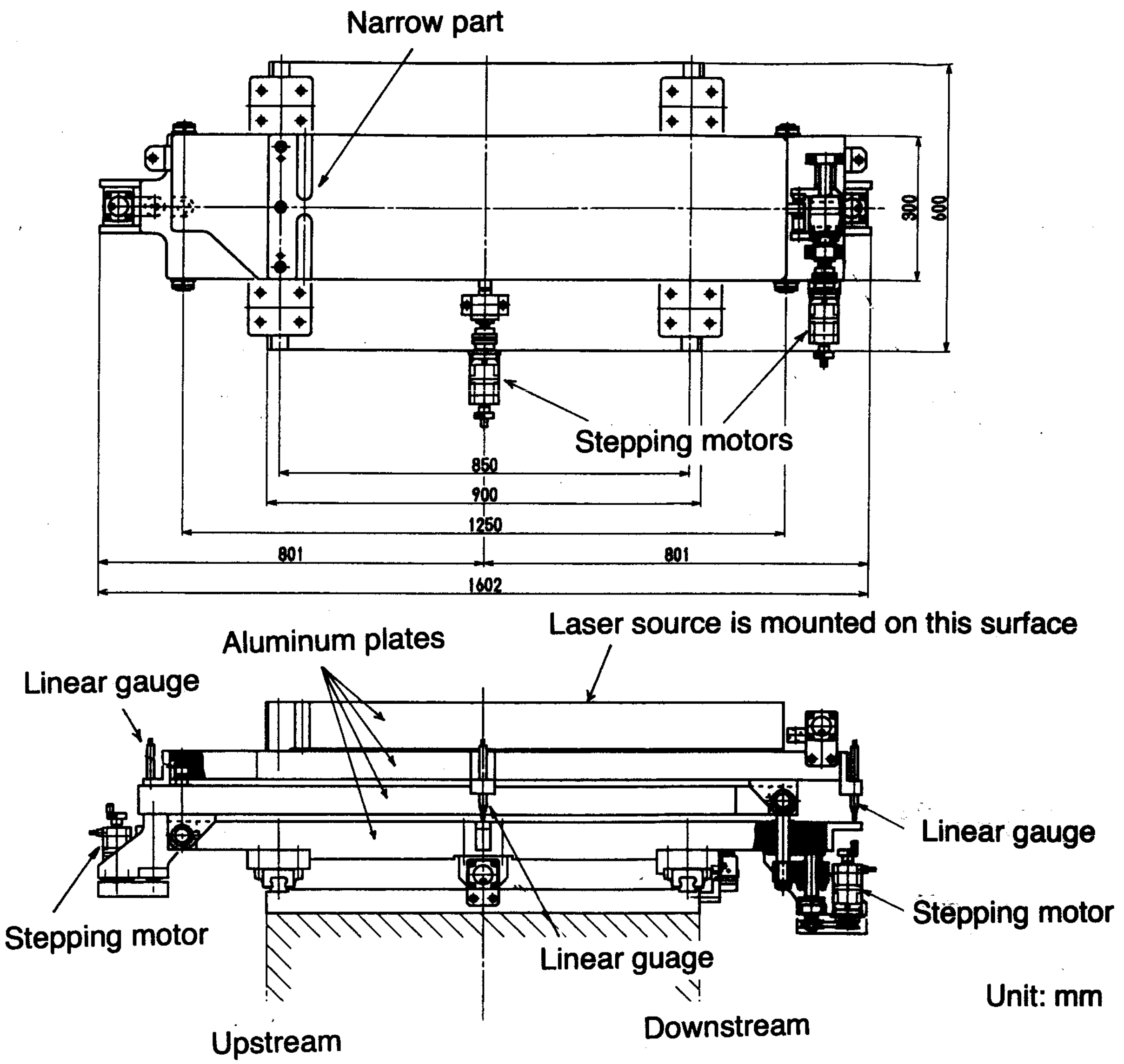


Fig. 6 Drawing of the laser stage.

linac part and that for the L3BT arc section is now under consideration. In any case, the laser stage is required to have a mechanism to adjust the light direction with extremely high resolution, namely, around 0.1 μrad. To realize the high-resolution direction control, we have adopted a deformation method. In the laser stage, the optical system is placed on aluminum plates, and each plate has a narrow part about which we can bend the plate easily. We elastically deform the plates to change the light direction by pushing the plates with stepping motors.

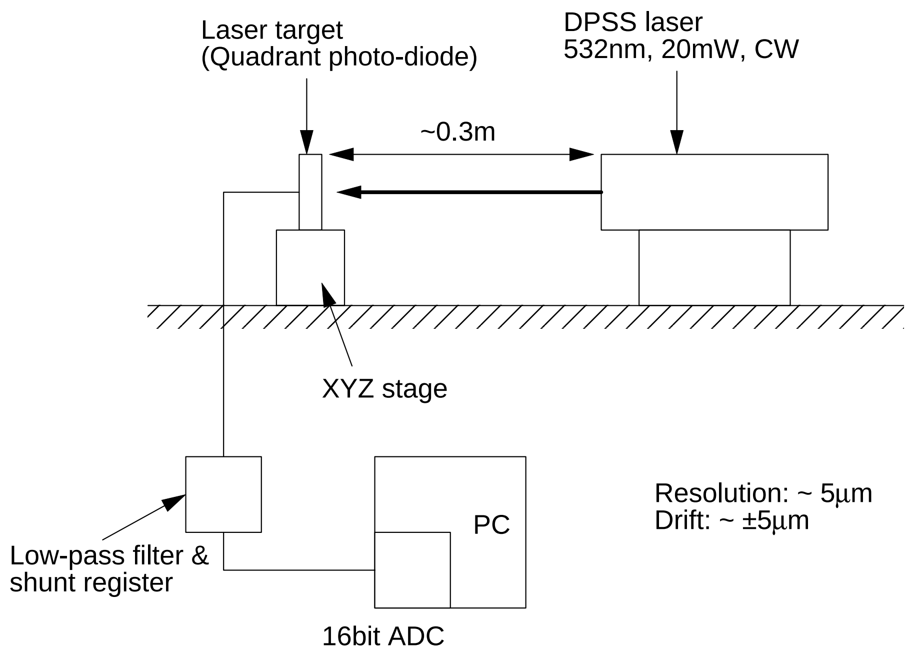


Fig. 7 Set up of the short-range experiment.

Research and development of the laser stage is now underway. This direction control system is expected to be useful in the initial alignment also.

2. EXPERIMENTS AT A TEST BEAM LINE

To check the feasibility of the laser-based alignment system, we have perform a long-range experiment with a 50 m long test beam line placed in the JHF linac accelerator tunnel at KEK. The main aims of this experiment are to examine the effect of air turbulence, and to check the performance of trial-manufactured components such as the laser target, the laser target box, the signal-processing unit, and the laser stage.

Before proceeding to the long-range experiment, we performed a experiment with much shorter beam propagation length to check fundamental characteristics of the laser target and the signal-processing unit, such as spacial resolution of the photo-diode, long-time drift of the A/D converter, etc. Figure 7 shows the experimental set up of the short-range experiment. The measured linearity of the laser target is shown in Fig. 8. The beam diameter at the laser target position is around 1 mm. The processed laser-target outputs Δ_H and Δ_V are shown in Fig. 8 as a function of the horizontal position of the XYZ stage on which the laser target is mounted. We readily see in Fig. 8 that the processed output is proportional to the displacement with a reasonable linearity in the range of about $\pm$0.5 mm. Although some non-linearity appears at around $\pm$1 mm, we have concluded that it does not cause a practically serious problem because the accuracy of the rough alignment, preceding the laser alignment, is expected to be better than

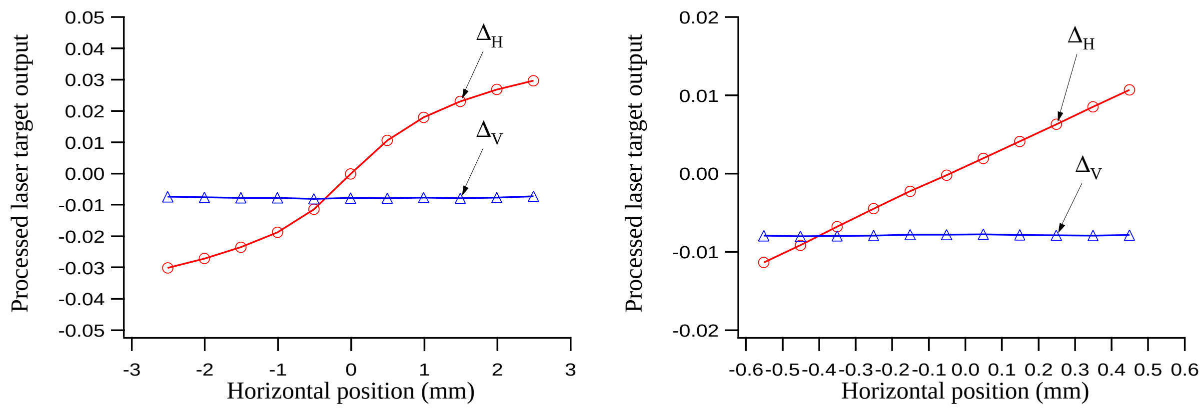


Fig. 8 Linearity of the laser target output. Vertical axis shows the processed laser target outputs Δ_H and Δ_V, which is dimensionless. Circles show the horizontal output Δ_H, and triangles show the vertical one Δ_V. Horizontal axis shows the horizontal position of the XYZ stage on which the laser target is mounted. The right figure is a close-up view of the left one.

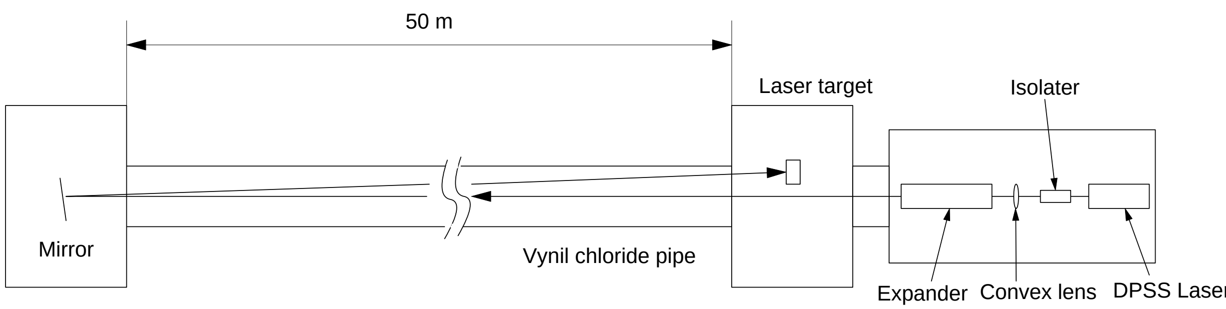
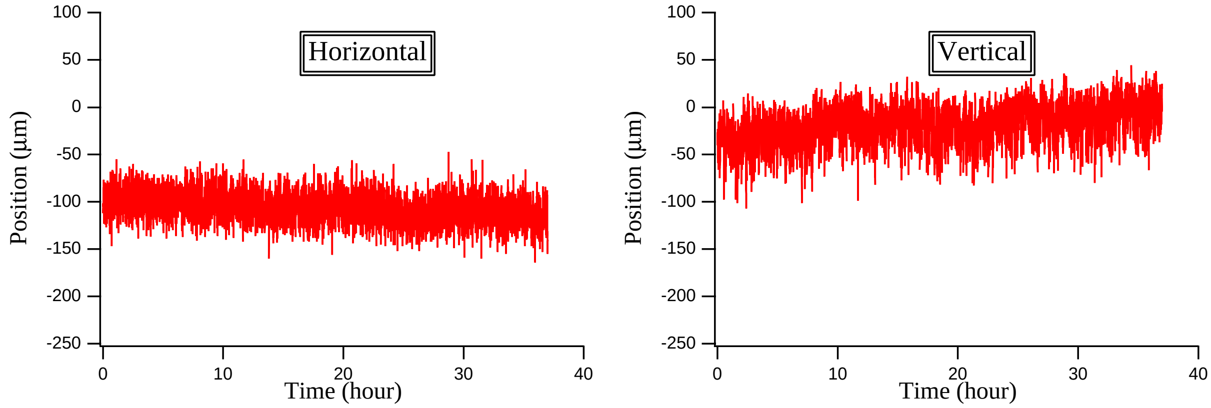


Fig. 9 Set up of the long-range experiment.

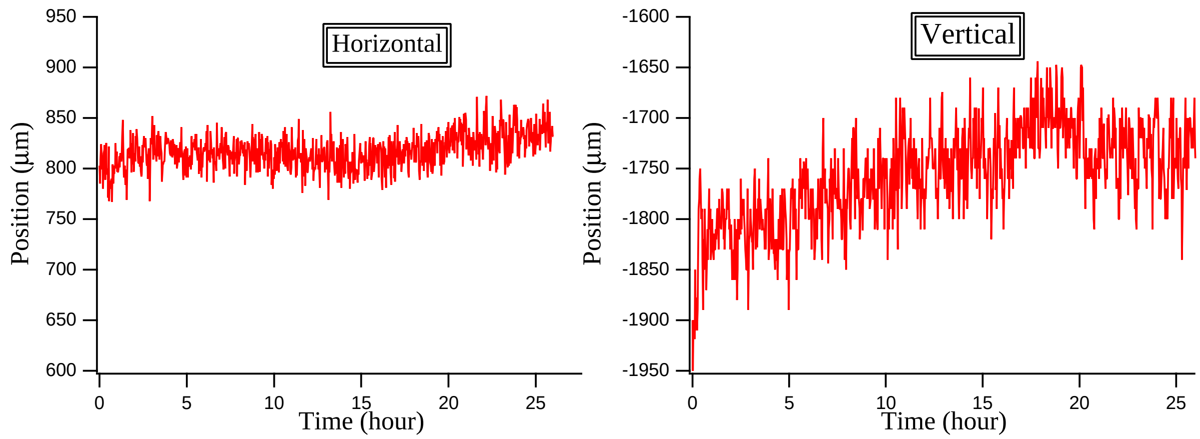
±1 mm. In the experiment, we concluded that the spatial resolution of 5 μm can be achieved, and the effect of the long-time drift of the A/D converter is around ±5 μm.

Figure 9 shows the experimental set up of the long-range experiment. At the upstream end, a laser source and an optical system are placed on the laser stage. The optical system we used in the experiment is simplified one which consists of a beam expander and an optical isolator, and neither collimator nor optical fiber is used. The laser pathway is surrounded by an air-tight duct made with vinyl chloride to ease the sway by air turbulence. The inner diameter of the air-tight duct is 150 mm. The air-tight duct is temporal. We plan to use stainless-steel or aluminum pipe in the actual alignment. At the downstream end, we have an optical stand on which we place a laser target for 50 m measurements, or a mirror for 100 m measurements. The tunnel is air-conditioned and a cooling-water system is operated during the measurements. No temperature control is applied for the laser source.



Average time: ~30 sec

Fig. 10 Time-evolution of measured laser position (50 m).



Average time: ~ 2 min

Fig. 11 Time-evolution of measured laser position (100 m).

Figure 10 shows the result of a 50 m measurement, in which measured laser-spot position is shown as a function of time. The result for 100 m measurement is shown in Fig. 11. It is seen in these figures that the output signal is composed of relatively fast sway component whose period is around or shorter than a few minutes, and slow sway, or drift, component whose period is longer than a few hours. The relatively fast component can be reduced with averaging. In Fig. 10, the output signal is averaged over 30 seconds, and 2 minutes in Fig. 11. We have found in the experiment that the amplitude of the fast sway is roughly proportional to the path-length in this setup, and that we need three- to four-times longer averaging time to reduce the amplitude to half. It is seen in Fig. 10 and Fig. 11 that the measurement resolution of less than ±50 μm can be achieved except for the vertical direction in the 100 m measurement. We suspect that the 100 m measurement is affected by some instability of the optical stand on which a mirror is placed, because the large-amplitude turbulence is not seen in 50 m measurement and suddenly arises in 100 m cases. Because even a slight tilt of the optical stand can affect the measurement in this setting, the system is very sensitive to the stability of the optical stand in the 100 m measurements. To have more conclusive results in 100 m measurements, we need to improve the optical system at the 50 m point.

The main causes of the sway are supposed to be the effect of air-turbulence and the pointing stability of the laser source itself. Long-term deviation of the temperature distribution in the tunnel may contribute to the slow sway. The pointing stability is expected to be improved by introducing a collimator or a single-mode optical fiber just after the laser source. The effect of air-turbulence is expected to be reduced by strengthening the air-tightness especially around the laser stage. Because the laser source has a cooling fan, the air-tightness around the laser stage is not so strong in the present set up. A possible way to strengthen the air-tightness is to adopt an optical fiber and to place the laser source somewhere far from the laser stage. To place the laser source far from the beam line is also important from the view-point of reducing the risk of radiation damage of the laser source. A test of an optical system with an optical fiber has been started.

As mentioned earlier, the fast component of the sway can be reduced by averaging. Contrary, it is difficult to reduce the slow sway or drift component. While the slow component observed in the experiment is within a tolerable level, that in the actual alignment can be more significant considering that the path-length is much longer and the stability may be strongly dependent on the tunnel environment. Therefore, we consider that it is urgent to perform further investigation on the cause of the slow component and find a way to reduce it.

3. CONCLUSION

We have developed a laser-based alignment system for the J-PARC linac. The trial-manufacturing of main components has been performed. The feasibility test with use of a 50 m long test beam line has also been performed with a simplified optical system. While sway of the laser spot has been observed, the required resolution of less than ± 50 μm can be achieved. However, it is still unclear if the required resolution and stability can be realized in the actual alignment, because the path-length and the tunnel environment are different. Especially, we need to perform further investigation on the cause of slow or drift component of the laser-sport sway.

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5. REFERENCES

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