

BEAM LOSS MITIGATION IN J-PARC LINAC AFTER THE TOHOKU EARTHQUAKE

M. Ikegami, K. Futatsukawa, Z. Fang, T. Miyao, Y. Liu, KEK/J-PARC, Tokai, Japan
T. Maruta, A. Miura, H. Sako, J. Tamura, G. Wei, JAEA/J-PARC, Tokai, Japan

Abstract

In the course of the beam commissioning of J-PARC linac after nine-month shutdown due to an earthquake, we have experienced beam losses which were not seen before the earthquake. One of the main cause for the beam loss was the irregular RF setting for accelerating cavities to avoid multipactor at one of them, which started to pose difficulty in the nominal operation after the earthquake. In this paper, we discuss the beam loss mitigation effort putting the emphasis on the optimization of the RF setting for SDTL.

INTRODUCTION

We had a magnitude-9.0 earthquake in Tohoku region in Eastern Japan in March 2011. It caused severe damage to J-PARC facilities which forced us to shutdown for nearly nine months [1]. After significant restoration efforts, we started beam operation of J-PARC linac in December 2011 and user operation in January 2012. The linac beam power when we resumed the user operation was 7.2 kW. Then, it is increased to 13.3 kW in March 2012, which is the same as just before the earthquake. While the linac beam operation was restored in terms of the beam power, we have experienced higher beam losses than before the earthquake. Thus, we have been trying to mitigate the beam loss while supporting the user operation. The initial beam start-up in December 2011 and January 2012 was reported in another literature [2]. Therefore, we focus on the beam loss mitigation effort after restoring the user operation in this paper. It should be noted here that the history of residual radiation during the beam commissioning was summarized in the reference [3].

J-PARC linac consists of a 50-keV negative hydrogen ion source, 3-MeV RFQ (Radio Frequency Quadrupole linac), 50-MeV DTL (Drift Tube Linac), and 181-MeV SDTL (Separate-type DTL) [4]. For later reference, we should note here that the SDTL section consists of 30 SDTL tanks with $2\beta\lambda$ inter-tank spacing with β and λ being the particle velocity scaled by the speed of light and the RF wavelength, respectively. Then, each SDTL tank consists of five β -graded cells, and two neighboring SDTL tanks are driven by a klystron.

As reported in reference [2, 3], we experienced significant beam loss at the straight section after SDTL immediately after we resumed the beam operation. A main cause of the beam loss was identified to be insufficient alignment of some of the beam ducts. After conducting urgent realignment of the beam ducts [5], the beam loss was sub-

stantially reduced and become significantly less sensitive to the beam steering. However, multipactor of one of SDTL cavity has been gradually worsened and the irregular RF setting we adopted to avoid the multipactor started to cause beam losses.

In this paper, we mainly discuss the method we adopted to circumvent the SDTL multipactor while suppressing the beam losses.

MULTIPACTOR AT AN SDTL CAVITY

As mentioned above, a pair of SDTL tanks are driven by a klystron. The relative RF amplitude and phase of the tank pair are supposed to be kept balanced with the low-level RF control system. However, we noticed just before the resumption of beam operation in December 2011 that the fifth tank pair, or SDTL5, shows some unstable behavior. For this tank pair, one of the tanks tends to have arcing, or presumably multipactor, which makes the balance of RF amplitude and phase easily lost. This unstable behavior arises in a certain range of RF amplitude which contains its design amplitude. Although similar behavior has been noticed for SDTL1 to SDTL6 since before the earthquake, it caused no difficulty in operating with the design tank level [6]. Therefore, we suspect that the multipactor in SDTL5 become severer at the earthquake for some reason to cause practical difficulty in the nominal operation.

As we can avoid the multipactor by adopting higher or lower RF amplitude for SDTL5, we adopt 109 % of the design amplitude in starting the user operation in January 2012. The unstable band in the RF amplitude was widened during the beam operation and forced us to increase the operating amplitude to 116 % later. As of June 2012, we are operate SDTL5 with the same amplitude. However, the unstable region for SDTL5 is still widening gradually and reducing the operational margin.

We don't delve into the details on the multipactor itself in this paper. Instead, we discuss the irregular RF setting for SDTL we adopt to avoid the multipactor, its effect on the beam losses, and the countermeasure for the beam loss we adopted in the beam commissioning. Further detail of the multipactor will be found in the reference [7].

BEAM LOSS MITIGATION WITH IRREGULAR SDTL SETTING

Operation with 109 % Amplitude for SDTL5

In setting the RF amplitude and phase for SDTL tanks after the earthquake, it was required for us to perform the

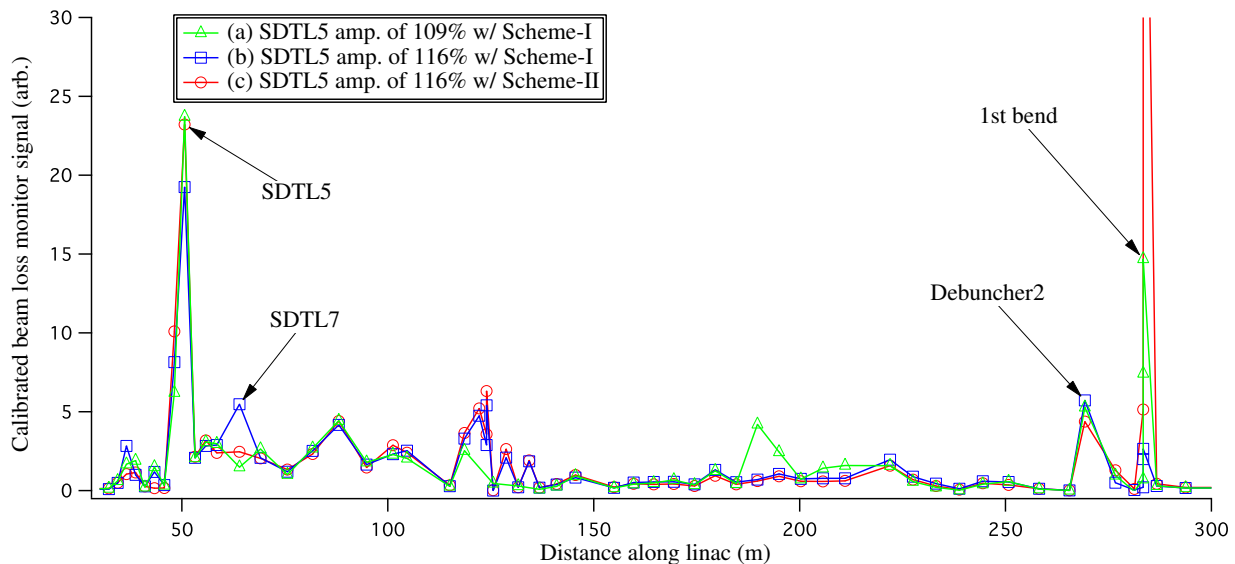


Figure 1: Calibrated beam loss monitor signal distribution along J-PARC linac and the following straight line of the beam transport line. Each marker shows the measured data with a beam loss monitor. The data are taken (a) with the SDTL amplitude of 109 % after Scheme-I tuning, (b) with the SDTL amplitude of 116 % after Scheme-I tuning, and (c) with the SDTL amplitude of 116 % after Scheme-II tuning.

phase and amplitude scan tuning [8]. At first, we adopted the RF amplitude of 109 % for SDTL5 to avoid the multipactor. In the phase and amplitude scan tuning, we needed an unusual treatment for SDTL5. Namely, we fixed the amplitude for SDTL5 and performed the phase scan only to find the phase setting to realize the design energy gain. After conducting the tuning for SDTL5, the tuning for SDTL6 and downer stream tanks were performed with the nominal procedure to set them to the design amplitude and synchronous phase.

After finishing the phase and amplitude scan tuning, we tried to operate with the determined RF setting. However, we experienced significant beam loss particularly at the straight section after the SDTL exit. We then tried to mitigate the beam loss by adjusting only the SDTL phases, because neighboring tanks also has unstable bands in their amplitude. In this tuning, we adopt the phase shift for SDTL5 and that for SDTL6 to SDTL15 as two tuning knobs. It should be noted that we assume the same phase shift for SDTL6 to SDTL15. This tuning was performed with the trial-and-error method to minimize the beam loss downstream with the phase-and-amplitude scan tuning result as the starting point. As a result, the phase for SDTL5 was shifted by +5 degree and those for SDTL6 to SDTL15 by -8 degree. Here, the positive phase shift is defined to increase the energy gain in the vicinity of the design phase. We call this tuning “Scheme-I” in this paper.

In the tuning, the beam loss is measured with BLM’s (Beam Loss Monitors) of gas proportional counter type [9] distributed along the linac. As the output from BLM tends to saturate, we perform a calibration to linearize it [10]. The calibrated BLM signal after the Scheme-I tuning is

shown in Fig. 1 as case (a). In the SDTL section with the horizontal axis of 30 to 115 m, the BLM is affected by X rays from SDTL cavity. A large peak is noticed at around 50 m, which is supposedly caused by X rays from SDTL5 operating with higher RF amplitude than usual. Another peak at around 280 m is the beam loss at the first bending magnet in the beam transport line. A large BLM signal there is often attributable to proton component generated in double stripping of negative hydrogen ions [10]. A peak at around 270 m is the beam loss at the second debuncher. As the aperture of the debuncher cavity is narrower than the neighboring beam transport lines, the beam loss naturally tends to concentrate on this location [11]. Aside from these peaks, a peak is also noticeable at around 190 m which is connected with significant residual radiation in the beam transport. This peak shows the beam loss caused by insufficient alignment of beam ducts which was avoided by re-alignment later. While a clear peak is not observed, we also had significant residual radiation at around 120 m. As the corresponding beam loss was not detected by the BLM’s which then existed, we added BLM’s in this area for later measurements (case (b) and (c) in Fig. 1).

Operation with 116 % Amplitude for SDTL5

While the beam loss was reasonably suppressed with a Scheme-I tuning for 109 % SDTL5 amplitude, gradual widening of the multipactor band of SDTL5 forced us to further increase its amplitude to 116 %.

With 116 % amplitude for SDTL5, we first tried Scheme-I tuning as in the previous subsection. However, we could not find a setting to fully suppress the beam loss this time. When we suppress the beam loss after the SDTL

exit, the beam loss in the middle of the SDTL section arises. Assuming the beam loss with lower energy would be preferable as the resultant residual radiation could be lower, we decided to adopt the setting to localize the beam loss at the upstream portion of the SDTL section. The resultant phase shift for SDTL5 was -6 degree and that for SDTL6 to SDTL15 was +8 degree. With this setting, the beam loss after the SDTL exit is comparable to before the earthquake, but we have visible beam loss at around SDTL7. It should be noted that the resultant phase shift is opposite to that in the previous subsection.

The beam loss distribution after the tuning is shown in Fig. 1 as case (b). In this figure, the peak at around 190 m was disappeared thanks to realignment. While the corresponding measurement with the same BLM configuration is not available for case (a), the peak at around 120 m was supposedly reduced judging from the reduction in the residual radiation [3]. Instead, a new peak arose at SDTL7 around 65 m as discussed above.

Operation with Design Longitudinal Focusing

After a certain period of user operation, we found that the beam loss at around SDTL7 caused significant residual radiation [3]. It motivated us to try an alternate scheme, namely, adoption of an optics with the design longitudinal focusing strength.

Keeping the design longitudinal focusing with increased RF amplitude, we naturally have higher energy gain. Consequently, we need to reduce the energy gain for neighboring cavities to compensate it. As mentioned above, we have multipactor for SDTL1 to SDTL6, which poses a constraint in choosing their RF amplitude. We conducted RF measurements to confirm that we can decrease the SDTL4 amplitude while avoiding the multipactor. Then, we tried an RF setting where we keep the longitudinal focusing for SDTL5 to the design strength with 116 % amplitude. Its excess energy gain is compensated by lowering SDTL4 amplitude. In this setting, the longitudinal focusing for SDTL4 is also kept to the design strength. We here call this tuning "Scheme-II". In calculating the longitudinal focusing force, we adopt the single gap approximation for SDTL4 and SDTL5 neglecting the phase slip. In the setting, the energy gain of SDTL5 is increased from the design value of 8.35 MeV to 10.00 MeV. Meanwhile, the energy gain of SDTL4 is decrease from its design 7.55 MeV to 5.90 MeV with the reduced amplitude of 83 %.

After adopting this setting, the beam loss was significantly reduced and become comparable to that before the earthquake. The beam loss at around SDTL7 disappeared by adopting this setting as shown as case (c) in Fig. 1. As seen in this figure, the beam loss at the first bending magnet around 280 m suddenly increased. While the reason for the sudden increase has not been fully understood, the beam loss was identified to be caused by protons and successfully mitigated by adjusting the chicane orbit we set up between RFQ and DTL [10].

SUMMARY

We had a large earthquake in March 2011 followed by a nine-month beam shutdown for restoration efforts. We resumed the beam operation of J-PARC linac in December 2011 and user operation in January 2012. Then, we recovered the beam power just before the earthquake in March 2012.

In the course of the beam commissioning, we have experienced beam losses which were not observed before the earthquake. Particularly, the multipactor in SDTL5 forced us to adopt irregular RF setting and it caused excess beam loss. In an effort to mitigate the beam loss, we have experimentally confirmed that we can suppress the beam loss by adopting an optics with the design longitudinal focusing. Although it may be an expected result, it would be a rare experimental demonstration because a high intensity β -graded linac is rarely operated with irregular RF setting for a long term. We have observed certain increase of the residual radiation at the second debuncher (not detected with BLM)[3] which might be attributable to the SDTL setting. Even with this reservation, this result provides valuable information in designing a counter-failure scenario for present and future high intensity linacs.

Thanks to the RF tuning and other efforts, we succeeded in reducing the beam loss in J-PARC linac to a comparable level to before the earthquake.

REFERENCES

- [1] K. Hasegawa, "Recovery of the J-PARC Linac from the Earthquake", in these proceedings.
- [2] M. Ikegami et.al., "Beam Start-up of J-PARC Linac after the Tohoku Earthquake", IPAC'12, New Orleans, May 2012, TH-PPC010, p. 3293 (2012).
- [3] M. Ikegami et.al., "Beam Commissioning of J-PARC Linac after Tohoku Earthquake and Its Beam Loss Mitigation", to be published in Procs. of 9th Annual Meeting of Particle Accelerator Society of Japan.
- [4] Y. Yamazaki ed., "Technical Design Report of J-PARC", KEK Report 2002-13 (2003).
- [5] J. Tamura et.al., "Beam Loss Reduction by the Beam Duct Realignment in the J-PARC Linac Beam Transport Line", to be published in Procs. of 9th Annual Meeting of PASJ (Particle Accelerator Society of Japan) (in Japanese).
- [6] T. Ito, K. Hirano, private communication.
- [7] T. Ito, K. Hirano, K. Nammo, "Multipactor at SDTL Cavity in J-PARC Linac", to be published in Procs. of 9th Annual Meeting of PASJ (in Japanese).
- [8] G. Shen, M. Ikegami, Nucl. Instrum. Meth. Phys. Res. A 598 (2009) 361.
- [9] S. Lee, M. Tanaka, T. Toyama, J. Kishiro, "The Beam Loss Monitor System of the J-PARC Linac, 3 GeV RCS, and 50 GeV MR", EPAC'04, Lucerne, July 2004, THPLT074, p. 2667 (2004).
- [10] H. Sako, M. Ikegami, IEEE Trans. Nucl. Sci., 57 (2010), 57.
- [11] T. Maruta, "Beam Loss Study at J-PARC Linac by Using GEANT4 Simulation", IPAC'11, San Sebastián, September 2011, WEPS047, p. 2595 (2011).