BEAM COMMISSIONING OF J-PARC LINAC AFTER TOHOKU EARTHQUAKE AND ITS BEAM LOSS MITIGATION

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Abstract

The beam operation of J-PARC linac was interrupted by the Tohoku earthquake in March 2011. After significant effort for its restoration, we have resumed the beam operation of J-PARC linac in December 2011. After the resumption of beam operation, we have been suffering from beam losses which were not observed before the earthquake. Tackling with the beam loss issues, we have been reached the same beam power for user operation as before the earthquake. In this paper, we present the experience in the beam start-up tuning after the earthquake with emphasis on the beam loss mitigation efforts.

INTRODUCTION

J-PARC is a high intensity proton accelerator facility which consists of a 181-MeV linac, 3-GeV RCS (Rapid Cycling Synchrotron), and 30-GeV MR (Main Ring). The injector 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) as shown in Fig. 1 [1]. We also have beam transport lines between the ion source and RFQ (LEBT or Low Energy Beam Transport), between RFQ and DTL (MEBT, or Medium Energy Beam Transport), and after SDTL (L3BT, or Linac-to-3-GeV Beam Transport). The locations of these beam transport lines are also shown in Fig. 1 for later reference.

Since the commencement of its user operation in December 2008, the beam power of the J-PARC linac has been gradually increased and reached 13.3 kW in November 2010. The beam power corresponds to the RCS beam power, or the beam power on the neutron target, of 200 kW. However, 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 [2, 3]. After significant restoration efforts, we started beam operation of J-PARC linac in December 9, 2011. The start-up of J-PARC accelerators was performed in two commissioning runs, one in December 2011 and the other in January 2012. The beam time allocated to the linac start-up was 8 days in the December run, and 6 days in the January run. The objective for the December run was to confirm the integrity of the linac and to supply the beam for the beam commissioning of downstream accelerators for a similar purpose with the minimum beam power. Then, that for the January run was to establish the beam parameters to sustain the high duty factor user operation. We succeeded in accelerating the beam to the design energy of 181 MeV and providing it to downstream facilities in December run. Then, we started the user operation in January 24, 2012 after conducting precise tuning of operating parameters. The linac beam power when we resumed the user operation was 7.2 kW. The beam power was then increased to 13.3 kW on March 15, 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. Then, 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 [4]. Therefore, we focus on the beam loss mitigation effort after restoring the user operation in this paper.

Before discussing the beam loss in the beam start-up after the earthquake, we review the beam loss situation before the earthquake in the next section. Then, two main issues regarding the beam loss in the beam start-up are identified. Subsequently, we describe our beam loss mitigation effort with history of residual radiation doses at some characteristic locations in the linac.

BEAM LOSS SITUATION BEFORE THE EARTHQUAKE

Before the earthquake, we had performed user operation with the linac beam power of 13.3 kW. Then, we had residual radiation widely distributed over the straight section after SDTL. The typical radiation dose was around or less than 0.5 mSv/h on the vacuum chamber surface several hours after beam shutdown. It should be noted that

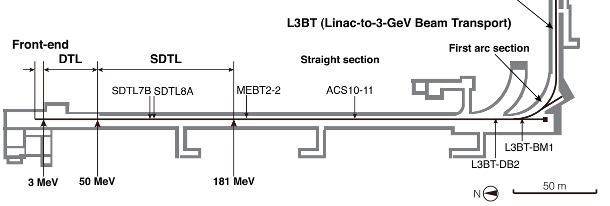

Figure 1: Schematic layout of J-PARC linac. Some locations where we experienced higher radiation dose in the beam commissioning (denoted by SDTL7B, SDTL8A, etc.) are also shown for later reference.

the radiation dose at one foot distance is typically lower by one order of magnitude, and the experienced radiation dose does not pose immediate threat over hands-on maintenance of the linac components. We have a narrow section at the entrance of the second debuncher, and we usually have the highest residual radiation dose in the linac there. It was typically 0.8 to 1.0 mSv/h with the same measurement condition. The beam loss we then experienced was insensitive to the beam tuning, specifically to the beam orbit steering. We made some experiments and concluded that the beam loss was mainly caused by neutral hydrogen, or H^0, generated due to the electron stripping of negative hydrogen ions in scattering with the residual gas [5, 6].

TWO MAIN ISSUES

We have two main issues regarding the beam loss in the beam commissioning of J-PARC linac after the earthquake. One is the insufficient alignment of beam ducts in the straight section after SDTL. The other is the unstable behavior of an SDTL cavity and irregular RF setting to avoid it.

Insufficient alignment of beam ducts

When the BLM's (Beam Loss Monitors) started to work properly in the initial beam start up after the earthquake, we noticed significant beam loss in the straight section after SDTL (See Fig. 2). We immediately found that the beam loss was sensitive to the beam orbit adjustment. Then, it was realized that the beam loss mechanism was completely different from before the earthquake. After optimizing the beam orbit, the beam loss was significantly reduced as seen in Fig. 2. However, the beam loss level was still higher than before the earthquake. Especially, the beam loss from 190 to 200 m was significantly high. Here, the location in the beam line is indicated with the distance from the RFQ exit, and the same definition is adopted for the horizontal axis in Figs. 2 to 4. The resultant optimum beam orbit shows the distortion of as large as ± 5 mm in the vertical direction, and + 2 to - 4 mm in the horizontal direction as shown in Fig. 3. As the beam orbit distortion in the nominal operation is typically less than ± 1 mm, the orbit distortion was significantly large. We identified the cause of this beam loss to be insufficient alignment of some beam ducts in the straight section. It was mostly solved by conducting urgent realignment in a short beam shutdown in February 2012. Details on the alignment measurement of the beam ducts and its realignment are discussed in another literature [7].

Although it was difficult to reduce the beam loss from 190 to 200 m by adjusting the beam orbit, we found that the beam loss at that area was sensitive to the phase setting for SDTL5 as seen in Fig. 4. The SDTL5 was tried because its behavior was unstable as discussed in the next subsection. This finding motivated us to pursue the phase optimization for SDTL to cope with the beam loss due to irregular SDTL setting discussed later.

Unstable behavior of an SDTL cavity

In SDTL section, we have 30 SDTL tanks and the neighboring two tanks are driven by one 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 arching, 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 [8]. Therefore, we suspect that the arching in SDTL5 become severer at the earthquake for some reason to cause practical difficulty in the nominal operation.

As we can avoid the unstable behavior by adopting higher or lower RF amplitude for SDTL5, we adopted 109 % of the design amplitude in starting the user operation in January 2012. However, the unstable region widened during the beam operation and forced us to increase the operating amplitude to 116 % in March 2012. We show the RF amplitude as the ratio to its design value in this paper. As of June 2012, we are still operating 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 unstable behavior itself in this paper. Further detail of the arching problem will be found in the reference [9, 10]. We tried to optimize the RF setting for SDTL to minimize the beam loss due to irregular amplitude setting for SDTL5. We briefly outline the effort in the next section leaving the detailed discussion for another literature [11].

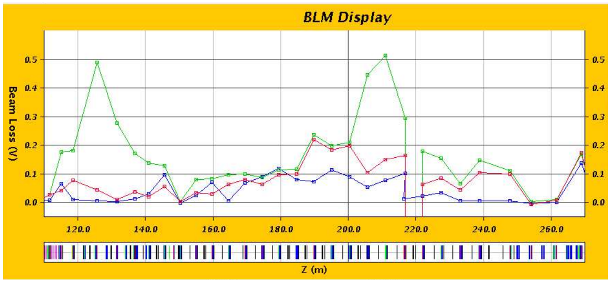

Figure 2: Beam loss monitor signal vs the distance along the linac. The beam loss was measured just after the beam loss monitors started work on December 13, 2011 (green), after beam orbit optimization on December 17, 2011 (red), and before earthquake on January 7, 2011 (blue). The exit of SDTL locates at around 115 m in the horizontal axis. The same definition is adopted for Fig. 3 and 4 for the horizontal axis.

Table 1: The history of residual radiation dose at the vacuum chamber surface several hours after beam shutdown in mSv/h. Unusually high radiation dose is highlighted with bold-faced type. Data in the rightmost column are taken on November 29, 2010. All the other data were taken in the year 2012. The locations denoted as MEBT2-2 and ACS10-11 were located in the straight section after SDTL, SDTL7B and SDTL8A in the middle of the SDTL section, L3BT-DB2 the entrance of the second debuncher, and L3BT-BM1 the first bending magnet in the beam transport. The locations for these measurement points are also shown in Fig. 1. No measurement data is available for a blank field.

Location	**Jan. 4**	**Jan. 26**	**Feb. 7**	**Feb. 22**	**Mar. 15**	**Mar. 22**	**Apr. 11**	**Apr. 20**	**May 16**	**May 25**	**Jun. 20**	**Before earthquake**
MEBT2-2	**4.3**	1.5	2.2	**8.0**	1.5	1.0	0.70	1.0	0.77	0.40	0.60	0.50
ACS10-11	**3.6**	2.0	2.5	**10**	2.5	2.5	1.8	1.8	1.1	1.0	1.1	0.60
SDTL7B	<0.05	<0.05	<0.05	<0.05	**1.4**	**3.4**	0.68	0.75	0.28	0.37	0.27	<0.05
SDTL8A	<0.05	<0.05	<0.05	<0.05	**2.0**	**3.0**	0.41	0.43	0.16	0.30	0.26	0.05
L3BT-DB2	0.08	0.11	0.23	0.22	0.33	0.64	0.65		**1.4**	**1.6**	**1.8**	1.0
L3BT-BM1		0.03	0.06	0.05	0.02		0.02	**0.67**	**2.6**	**1.6**	0.24	

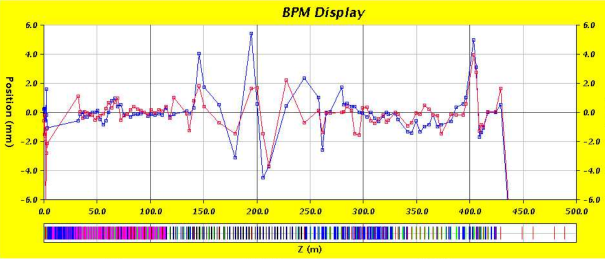

Figure 3: Beam position monitor signal vs the distance along the linac. The beam position was measured after the beam orbit optimization on December 17, 2011. The horizontal beam position is shown in red, and vertical in blue.

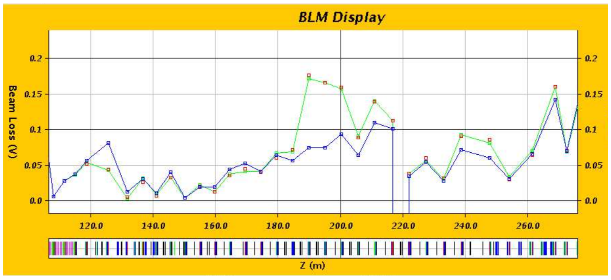

Figure 4: Beam loss monitor signal vs the distance along the linac. The beam loss was measured before (green) and after (blue) adjusting SDTL5 phase. Both data were taken on December 19, 2011. It should be noted that we should not make direct comparison of the beam loss level with Fig. 2 because of difference in the beam duty factor in these measurements.

BEAM LOSS MITIGATION

In the course of the beam start-up, we have experienced significantly higher residual radiation doses than before the earthquake at some locations. The history of the residual radiation doses observed at some of these points are summarized in Table 1. The residual radiation doses listed in this table were measured on the surface of vacuum chamber. Then, the measurements were performed several hour after beam shutdown except for the data on January 4. As mentioned above, we start the user operation on January 24 with the linac beam power of 7.2 kW, and then increased it to 13.3 kW on March 15. Before the commencement of the user operation, we performed the beam tuning with the lower duty factor. The linac beam power was typically 0.7 kW or less except for the 7.2-kW and 13.3-kW demonstration runs conducted on December 26 for a few hours. In addition, the first round of the beam commissioning was finished on December 27. Then, the data on January 4 were measured 8 days after the beam shutdown. Taking these conditions into consideration, the observed radiation doses at the straight section after SDTL (MEBT2-2 and ACS10-11 in Table 1) on January 4 are unexceptionally high.

Although it is difficult to make quantitative comparison between the results on January 4 and January 26, it would be fair to say that the fractional beam loss was significantly reduced in the tuning in early January. This difference would be attributable to the phase scan tuning conducted in this period and the trial-and-error optimization of phase setting for SDTL cavities. Nevertheless, the residual radiation dose gradually accumulated during the high duty factor user operation. Then, the residual radiation dose at the hottest spot (ACS10-11 in Table 1) reached 10 mSv/h on the vacuum chamber surface several hours after beam shutdown on February 22. This radiation level is the highest we have ever experienced in J-PARC linac.

We found that the cause of this residual radiation was the beam loss due to insufficient alignment of some beam ducts in the straight section after SDTL. Urgent realignment of the beam ducts was conducted in the interval from February 22 and 24. Thereafter, the radiation doses at those hot spots (MEBT2-2 and ACS10-11 in Table 1) started to decay. Meanwhile, we increased the SDTL5 amplitude from 109 % to 116 % after the same interval. With increased SDTL5 amplitude, it become difficult to suppress the beam loss by optimizing only the phase setting for SDTL. Visible radiation doses arose in the middle of SDTL section (SDTL7B and SDTL8A in Table 1) due to this irregular

SDTL setting.

To mitigate the beam loss, we adopted an optics with smoother longitudinal focusing at around SDTL5 after April 5. This smoother optics were realized by decreasing SDTL4 amplitude to 83 % and deliberately adjusting the phases for SDTL4 and SDTL5 to provide the design longitudinal focusing in both SDTL4 and SDTL5. The amplitude for SDTL5 was kept to 116 % to avoid instability. After this tuning, the residual radiation in the middle of SDTL section started to decrease. At the same time, we observed significant increase in the residual radiation at the entrance of the second debuncher (L3BT-DB2 in Table 1) and more significantly the first bending magnet in the beam transport after SDTL (L3BT-BM1 in Table 1). Although the reason for this sudden increase has not been understood, the rise in the beam loss at the first bending magnet is often attributable to the proton component generated with the double electron stripping in the residual gas scattering in LEBT [12]. Based on this supposition, we performed the re-optimization of the chicane orbit in MEBT to remove the proton component on May 26. Subsequently, the residual radiation dose at the bending magnet was significantly reduced.

Consequently, the residual radiation dose in the linac has become comparable to before the earthquake, while we are still experiencing higher doses at some locations. One of those locations is at the middle of the straight section (ACS10-11). We suspect that it may be attributable to residual misalignment of the beam duct. Another point with higher dose is the entrance of the second debuncher (L3BT-DB2). The reason for the increase is still open. However, the radiation doses at those points are not so significant that they won't pose any immediate threat on the beam power ramp up after summer shutdown. It should be noted that the narrow section at the second debuncher is to be removed in the energy upgrade scheduled in the summer 2013.

SUMMARY

We had a large earthquake in March 2011 followed by a beam shutdown for restoration efforts which was continued for nearly nine monthes. We resumed the beam operation of J-PARC linac in December 2011 and user operation in January 2012. We reached the linac beam power of 13.3 kW in March 2012, which is the same beam power as just before the earthquake. Then, it may be reasonable to conclude that we succeeded in swiftly restoring the linac operation in terms of the beam power.

After resuming the user operation, we however experienced beam losses which were not seen before the earthquake. Especially, we had severe beam losses and resultant high residual radiation dose in the beginning of the beam start up. We have continued the effort to mitigate the beam loss while supporting the user operation. It includes urgent realignment of some beam ducts, and optimization of RF setting for SDTL cavities to aviod the instability presumably caused by multipactor. Consequently, we succeeded in reducing the beam loss to a comparable level to before the earthquake. After the summer shutdown, we plan to continue the effort to further mitigate the beam loss in parallel with seeking higher beam power for user operation.

ACKNOWLEDGMENT

We gratefully acknowledge that the radiation dose in J-PARC linac shown in this paper was measured by the radiation safety group of J-PARC. We would also like to acknowledge that the swift restoration of J-PARC linac was realized by significant efforts of all the linac group members. The efforts were led by H. Oguri, N. Ouchi, and K. Hasegawa of JAEA.

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