BEAM START-UP OF J-PARC LINAC AFTER THE TOHOKU EARTHQUAKE

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

Abstract

The beam operation of J-PARC linac was resumed in December 2011 after a long shutdown due to damages by the Tohoku earthquake in March 2011. Subsequently, the user operation was also resumed in January 2012. In this paper, we present the experience in the beam start up after the earthquake.

INTRODUCTION

We had a magnitude-9.0 earthquake at Tohoku region in Eastern Japan in March 2011. While its epicenter was about 270 km far from the J-PARC site, it still caused a significant damage to the J-PARC accelerator facilities and forced us to shutdown the accelerator for a significant period of time [1]. As for the linac, the floor deformation [2] and the damage to the buildings on the ground were particularly severe. Due to the damage, all utilities become unavailable for months. While the RF cavities and magnets were not damaged in the earthquake, many beam monitors, most of which were FCT's (Fast Current Transformers) for beam phase measurement, were damaged and caused vacuum leaks [3]. We had many cracks in the accelerator tunnel, through which the ground water seeped. Then, the accelerating cavities were exposed to the air of high humidity for several weeks without air-conditioning. The recovery work involved realignment for almost all accelerator components. The realignment was performed in line with a specially designed plan [4], where the emphasis is put on swift recovery of beam operation tolerating the deflection of the beam line at the exit of DTL (Drift Tube Linac). We haven't performed the realignment of drift tubes inside the cavities. While urgent alignment measurement for drift tubes showed tolerable misalignment [5], the possibility of large misalignment of drift tubes and resulting reduction in the transmission efficiency or serious increase in the emittance were major concern.

After significant recovery efforts, we resumed the beam operation of J-PARC linac on December 9, 2011. Then, we restarted the user operation for neutron target on January 24, 2012. The user operation for fast-extracted and slow-extracted beams from MR (Main Ring) also started subsequently. The beam time allocated for the linac start up was 8 days in December and 6 days in January. The main objective for the December run was to deliver a low-duty-factor beam down to the neutron and neutrino targets to confirm the integrity of the facilities. That for the January run was to establish operation parameters to sustain high-duty-factor user operation. In this paper, the experience in the beam start up of J-PARC linac is described as a reference for future commissioning of high intensity linacs.

INITIAL ACCELERATION

J-PARC linac consists of a 3-MeV RFQ (Radio Frequency Quadrupole linac), a 50-MeV DTL, and a 181-MeV SDTL (Separate-type DTL) [6]. DTL consists of three tanks, and SDTL 30 tanks. We also have two buncher cavities in MEBT (Medium Energy Beam Transport) between RFQ and DTL, and two debuncher cavities after SDTL.

Prior to the resumption of the beam operation, we prepared an RF phase and amplitude setting for DTL and SDTL cavities to reproduce the cavity tank amplitude and the relative phase between the neighboring cavities before the earthquake. This setting was obtained with RF measurements as a starting setting for the beam-based phase and amplitude scan tuning [7, 8]. We assume that the accuracy of the preset setting is within 1 degree in phase and 1 % in amplitude with relative to the ones before the earthquake. The accuracy is supposed to be sufficient for the beam acceleration. As the preset setting was not available for buncher cavities due to absence of measurement data before the earthquake, we started the beam tuning with the phase and amplitude scan tuning for buncher cavities and DTL1 (1st DTL tank). We should note here that the phase for DTL1 is particularly sensitive to the injection energy due to relatively long drift spaces in MEBT, and hence deserves special attention.

In December run, we assumed the nominal peak current of 15 mA, but the reduced pulse width and repetition rate of 0.1 ms (one fifth of the design) and up to 2.5 Hz (one tenth of the design), respectively. We first confirmed adequate beam transmission through DTL and SDTL on December 9 with a 3-MeV beam accelerated only with RFQ (See Fig. 1). The 3-MeV beam is transported with the quadrupole strengths lowered to fit the magnetic rigidity. This setting is possible because we adopt electromagnets for DTQ's (Drift Tube Quadrupoles). We adopted a similar setting in delivering a 50 MeV beam discussed later.

After completing the phase and amplitude scan tuning for bunchers and DTL1, we achieved full acceleration to 181 MeV on December 10 using the preset setting for DTL2 and downer stream cavities. The phase scan for DTL2 was conducted only to determine the phase offset for DTL2 and downer stream cavities. It was the first time for us to achieve 181-MeV acceleration without fully conducting phase and amplitude scan tuning after a long beam shutdown.

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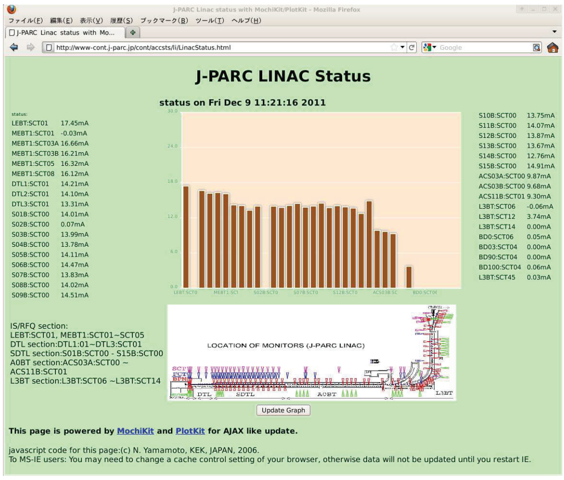

Figure 1: Snapshot of a web site which shows the beam current profile along the linac. The displayed profile is the one for the 3-MeV beam first delivered after the earthquake.

BEAM MONITOR CHECK

After achieving the 181-MeV acceleration with this temporal setting, we focused on confirming proper functioning of beam monitors. Especially, we paid significant efforts to check FCT's, because we updated the calibration parameters for almost all FCT's due to replacement of monitor heads and signal cables. The phase and amplitude scan tuning is performed while monitoring output energy by TOF (Time-Of-Flight) method using two FCT's. Then, the accuracy for FCT's is essential for the linac tuning. The consistency check of TOF pairs in the SDTL section was conducted using a 50 MeV beam accelerated up to DTL3 and delivered to the straight dump downstream. In this study, the energy of a 50 MeV beam is measured with various FCT pairs to find an inconsistent monitor.

In the course of the monitor check, we identified some malfunctioning FCT's. We spent significant beam time in trying to perform phase and amplitude scan tuning with available FCT's. However, we finally decided to operate with the temporal setting in December run instead of performing the phase and amplitude scan tuning for DTL2 and downer stream cavities. The problems in FCT's were mostly solved by recalibration conducted after December run, and the phase and amplitude scan tuning was successfully performed in January run. We should note here that unusual behavior of SDTL5 discussed later also posed additional difficulty in conducting the phase and amplitude scan tuning in December run.

BEAM LOSS

When BLM's (Beam Loss Monitors) started to work properly on December 13, we found significant beam loss in the straight section after SDTL. Before the earthquake, most beam loss was supposed to be caused by H^0 generated in the residual gas scattering of H^- beams [9]. However, the beam loss we found in the beam start-up was obviously caused by a different mechanism, because it was sensitive to the beam orbit in its vicinity. During January run, we identified two characteristic features of the beam loss. One was the tendency of the radiation dose to concentrate on branch ducts for vacuum pumps. The other was the lower residual radiation at downstream part than that before the earthquake. As the vacuum pressure level in the beam transport line was comparable to that before the earthquake, the H^0 yield should also be comparable. Therefore, the lower radiation dose downstream seemed to suggest smaller physical aperture somewhere upstream. Combining these observations, we decided to check the alignment of the branch ducts with a laser-tracker and found unexpectedly large misalignment of up to 16 mm with respect to the neighboring quadrupoles. It is comparable to the aperture radius of 20 mm for the beam transport line. As the beam width measured with a wire-scanner was typically around $\pm$ 8 mm, it was natural to have visible beam loss with such a large misalignment. As shown in Fig. 2, the branch duct locates in the middle of two quadrupole doublets with bellows at the upstream and downstream sides. Then, V-shaped misalignment can easily arise if you misalign the branch duct. We corrected the alignment after January run, and the residual radiation dose started to decrease.

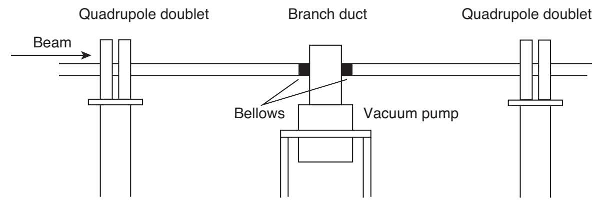

Figure 2: Schematic layout of beam ducts in the straight section after SDTL.

While the branch duct was originally aligned with a leveling string, the alignment accuracy was not quantitatively confirmed with a surveying instrument. The lack of confidence in the RF setting in December run also delayed the identification of the cause for the beam loss.

Before the realignment, we also observed a beam loss component localized at the head of a macro pulse, which was not observed before the earthquake. As shown in Fig. 3, the typical duration of the loss component was 1 μs. While the fast component disappeared after the realignment, it may indicate that the head of a macro pulse could have a different property from other part.

UNSTABLE BEHAVIOR OF AN SDTL CAVITY

In SDTL, two neighboring tanks are driven by one klystron, and we call a set of the klystron and tank pair an SDTL module. Immediately before December run, we noticed an unusual behavior of SDTL5 (the 5th SDTL module) where balance of the tank level and phase between the

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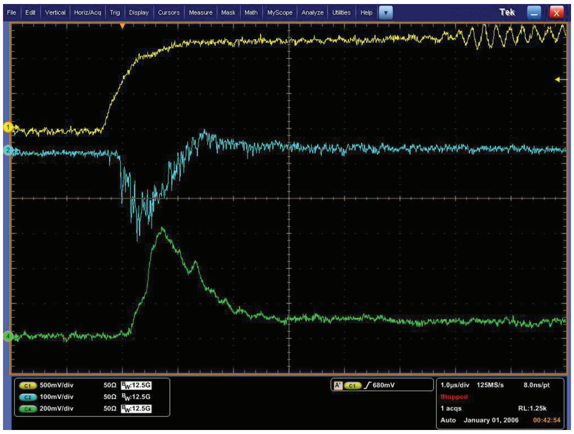

Figure 3: The waveform for a beam current monitor (yellow), a BLM of scintillator type (blue) and a BLM of gas-proportional counter type (green) in the beam straight line after SDTL. The full range in the horizontal axis is 10 μs.

tank pair was easily lost. In December run, we manually adjusted the tuner position for SDTL5 with particular care and operated it with its auto-tuner turned off so that we could manage to keep the balance. We have found that this unstable behavior is dependent on the tank level, and disappears with sufficiently higher tank level. Then, we decided to operate SDTL5 with 9 % higher tank level than design in January run as a temporal measure. The phase and amplitude scan tuning was performed with setting the SDTL5 phase to provide the design energy gain. After finishing the phase and amplitude scan tuning for all SDTL modules, we shifted the phase for SDTL5 to SDTL15 to minimize the beam loss in the straight section after SDTL. We assumed the same phase shift for SDTL6 to SDTL15, and conducted a trial and error tuning with two tuning knobs. As a result, the SDTL5 phase 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 if you operate in the vicinity of the design phase. We achieved the user operation with 7.2 kW linac beam power with this setting, which corresponds to 120 kW from the succeeding RCS (Rapid Cycling Synchrotron). We also confirmed that the transverse emittance at the linac exit was comparable to that before the earthquake with this setting.

We suppose that the unstable behavior is caused by multipacting in one of the SDTL5 tanks [10]. We have noticed multipacting in SDTL5 and neighboring SDTL modules since before the earthquake. However, it did not pose any difficulty in operating with the design tank level before the earthquake. Then, we suppose that the multipacting became severer after the earthquake for some reason. We suspect that change in the surface condition of the cavity due to exposure to the air is a possible cause.

SUMMARY

After the Tohoku earthquake in March 2011, we resumed the beam operation of J-PARC linac in December 2011. After two series of linac beam tuning extending to 14 days in total, we succeeded in resuming the user beam operation with the linac beam power of 7.2 kW in January 2012. The beam power was increased to 13.3 kW on March 15, which is the same with that just before the earthquake. Then, the situation before the earthquake has been restored in terms of the beam power. While we adopted deflections in the alignment axis in the realignment, we have seen no obvious effect to the beam quality so far. We have not seen deterioration of the beam transmission efficiency for DTL either, which had been a serious concern regarding possible misalignment for the drift tubes inside the DTL tanks. However, the unstable behavior of SDTL5 became worse during January run, and forced us to increase the SDTL5 tank level to 116 % of the design tank level. We are having higher residual radiation doses than those before the earthquake possibly due to this irregular SDTL setting. Further effort is now under way to mitigate the beam loss to the level before the earthquake.

ACKNOWLEDGMENT

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