RECOVERY OF THE J-PARC LINAC FROM THE EARTHQUAKE

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Abstract

J-PARC was severely damaged by the March 11 Great East Japan Earthquake in 2011. When the earthquake struck, we had a beam study operation of the linac, and the machine automatically stopped immediately. The damages to the facilities and infrastructure were very serious over the entire site. Thanks to the significant effort of restoration, we resumed beam operation in December 2011 and user operation in January 2012. We learnt many lessons from the earthquake.

INTRODUCTION

J-PARC, which stands for Japan Proton Accelerator Research Complex, consists of the linac, the 3 GeV rapid cycling synchrotron (RCS), the 30 GeV Main Ring synchrotron (MR) and three experimental facilities[1]. The linac consists of a negative hydrogen ion source, a 3 MeV RFQ (Radio Frequency Quadrupole linac), a 50 MeV DTL (Drift Tube Linac) and a 191 MeV SDTL (Separated-type DTL) as shown in Fig. 1. But currently, the last 2 SDTL cavities are used as debunchers with no acceleration, and then the injection energy to the RCS is 181 MeV. Construction of superconducting linac (SCL) from 400 to 600 MeV and experimental facilities for the Accelerator Driven Transmutation System (ADS) are planned in the next construction phase of J-PARC. A proton beam from the RCS is injected to Materials and Life Science Experimental Facility (MLF) for neutron and muon experiments. The MR has two beam extraction systems. One is a fast extraction for the neutrino beam line for the Tokai-to-Kamioka (T2K) experiment, and the other is a slow extraction for Hadron Experimental Facility.

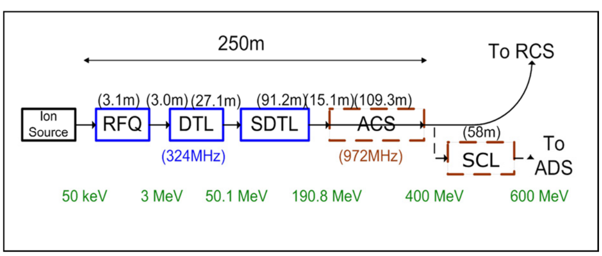

Figure 1: The structure of the J-PARC linac.

Coincidentally no user services were scheduled in the daytime of March 11, 2011. Beam study at the linac, and radiation survey work at the RCS and MR tunnels were carried out. The earthquake occurred when we suspended a beam for changing a beam destination from the linac to the RCS. The earthquake intensity was 6 lower at Tokai, which is the third highest intensity of the ten-ranked Japanese seismic scale. Whereas we prepared up to 8 m tsunami, the actual level was much lower at 3 m. It was extremely fortunate that no one was injured or missing.

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STATUS BEFORE THE EARTHQUAKE

Commissioning of the linac started in 2006 and entire accelerators started operation in 2009. We had a discharge trouble at the RFQ, but this was settled during the summer shutdown of 2009 by improving the vacuum system. Since then, we had kept stable operation for users, concretely 90 to 95% availability. We ramped up the beam power from the RCS to the MLF to 120 kW in the 2009 fall and then to 200 kW in November 2010. Corresponding linac beam power is simply calculated by the ratio of energy, 0.060=(181/3,000), e.g. 200 kW RCS power corresponds 12.0 kW linac power. At the MLF, many neutron beam lines were in operation and numerous data had been accumulated before the earthquake. We also performed 400 kW (equivalent current beam) acceleration for higher power demonstration in January 2011.

The MR had been increased beam power steadily and had delivered beam at 145 kW to the neutrino beam line. Muon neutrinos may convert to electron neutrinos while travelling J-PARC to the Super-Kamiokande detector in 295 km distance. Detailed study results before the earthquake revealed that there were 6 possible events of the appearance of electron neutrinos.

The MR slow extracted beam to the Hadron Facility was 3 kW. Many experiment just started and the first data of the penta quark search were obtained.

THE EARTHQUAKE DISASTER

The big earthquake with magnitude of 9.0 hit the northeastern Japan on March 11, 2011. The J-PARC is located at about 200 km from the epicenter and had significant damage. Because the status of the J-PARC facility in general is described in some references[2,3], this paper mainly focus on that of the linac.

Linac

The linac building had the most seriously damages among all other buildings. A wide area at the entrance of the linac building subsided about 1.5 m, and almost all water supply and drainage pipes were broken as shown in Fig. 2. We could not get into the building until March 17 due to many strong aftershocks. It was found that there were fortunately no severe damages on the accelerator components themselves, but found that water was accumulated by 1 cm in depth on the linac tunnel floor. When we entered the tunnel again a week later on the 24th, the water level increased to approximately 10 cm. The leakage speed in this week was much faster than that of the first week from the earthquake. Therefore, we

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decided to pump it out immediately. Because the electricity for the building had yet not been restored for the building, we used a diesel engine generator. In addition, because the leaked water that went through the

Figure 2: Subsidence near the entrance of the linac building. Water supply and drainage pipes were broken.

concrete wall was highly alkaline, we had to neutralize it by acids before draining it. It took two days to drain approximately 150 m^3 of water. When the floor exposed, numerous lateral cracks were recognized on the floor and the walls.

Thereafter our main concern was the damage from the flooding and high humidity. One was damage on vacuum pumps placed on the floor. We rinsed and dried the pumps first, and then turned them on after tested their insulation resistance. It turned out that eight pumps and four controllers out of 36 pumps were broken down. Small aluminium boxes for diagnostics pre-amplifiers on the floor also had been submerged, and had been corroded by strong alkaline water. Several beam monitors and bellows welded to beam transport pipes between the SDTL cavities were also damaged, due to strong vibration[4]. Consequently many cavities were exposed by air with high humidity.

Vertical and horizontal displacement of the tunnel floor was measured. It turned out that there was a deformation of 4 cm in vertical and 2.5 cm in horizontal directions.

The acceleration cavities, such as the RFQ, the DTL and the SDTL were checked through visual inspection, vacuum test, and measurement of resonant frequencies and Q factors. As a result, small vacuum leaks at some flanges were found but no RF property changes were recognized. Displacement of the drift tubes in the DTL and SDTL cavities was observed by an alignment telescope.

The building floor on the ground was also displaced in both vertical and horizontal directions. Some pillars inclined due to the damage of their bases. So we could not use most of the cranes.

RCS and MR

The damages of the RCS were mainly outside of the building. The surrounding road became wavy and we had to repair it first to access to the yard. There were many high power devices to be restored in the yard, such as chilling refrigerators, cooling towers, capacitors, transformers, and power distribution boards, etc. Because the yard subsided about 0.3 - 1 m at many places, we first jacked up the devices and put concrete underneath to be levelled the base. In contrast, we fortunately had few significant damages in the RCS building.

For the MR, groundwater leaked from cracks into the main tunnel, but the tunnel, except for a part of the sub-tunnel, did not flood. We had a detailed test throughout the ring, and fortunately, there were no leaks in the beam ducts. Inspection of main electromagnets was also performed. It appeared that there was significant displacement by 2 to 3 cm at the maximum in some places. All 400 magnets were realigned to the original positions. It was time-consuming work to restore the MR.

Experimental Facilities

The most serious problem was displacement of shield blocks at the MLF. We had to move out 2,800 tons of ion blocks near the neutron target and restacked piece by piece. It was time-consuming. The attached building for a long baseline of the neutron spectrometer sank approximately 30 cm compared to the main MLF building. We had to jack up this building to the same level as the main building.

There were many subsidence spots around the building of Neutrino Experimental Facility but fortunately very little damage was found in the main components.

Subsidence also occurred around Hadron Experimental Facility. Although serious damage was not found in the main components, there were many gaps between shielding blocks. We reloaded over 3,000 tons of blocks and restacked.

RESTORATION

We surveyed the total scale of the damage on the entire J-PARC facilities and investigated the technical possibility of early recovery. As a result, the J-PARC Center announced the restoration schedule in May 2011. The main points are as follows:

- We would start test operation with using beams in December 2011.
- We would restart the user program in January 2012 and would provide beams for users for two months in JFY2011.

To meet the schedule, we selected the higher priority items that were necessary for operation, experiments and safety, such as water sealing in the tunnel, realignment work, firewalls repair, etc. Not only hardware experts, but also beam simulation experts did their utmost to shorten the restoration period.

Figure 3 shows the displacement of the linac components such as cavities and magnets. There were about 40 mm and 25 mm displacements in vertical and horizontal directions, respectively. It is time-consuming work to move DTLs by several centimeters because a large number of heavy cables for electromagnets are connected. The estimated time for the realignment was about 6 months. We discussed a better scenario for the realignment of DTLs and also SDTLs to meet the restoration schedule with minimizing an effect on the beam degradation[5]. We decided to steer the beam at the downstream of the DTL section horizontally and vertically as shown as the dotted lines in Fig. 3. In the beam simulation, it appeared that this deflection of the alignment axis showed no effects on beam transmission and emittance degradation, because the steering angle was small in the order of 1 mrad or less.

Based on the measurement of displacement of the drift tubes, it appeared that there was 0.1 mm or 0.2 mm maximum misalignment for some drift tubes[6]. The particle simulation results also showed that the tolerable limit of the misalignment was ± 0.2 mm. Therefore, we concluded that the observed drift tube misalignment would not be critical and decided we would not realign the drift tubes at this time.

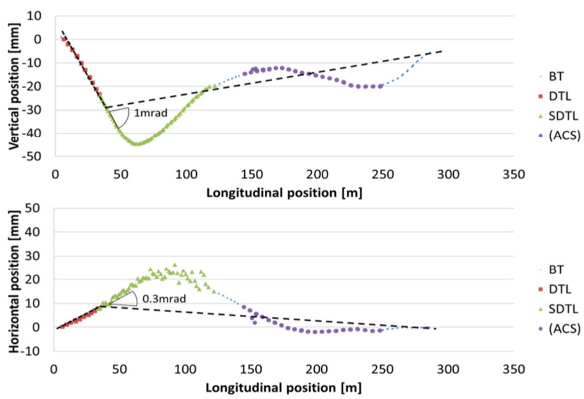

Figure 3: Displacement of the accelerator components after the earthquake (dots) and target realignment line (dashed lines).

BEAM OPERATION

Thanks to the effort of staff members and the support, the restoration work was accomplished on schedule. Before beam operation, the accelerating cavities were conditioned at high power RF for 24 hours a day from October 17 for the RFQ and from November 7 for the DTLs and SDTLs, respectively. It took a longer time than usual because some cavities were exposed to high humidity air. We started beam tuning at the linac on December 9, which was three days ahead of the detailed schedule established in September. Although many damaged things such as roads, cranes, doors, pillars, etc., had not been repaired yet, we could safely turn on the beam.

The purpose of the December's tuning was to check the operation processes from linac to the downstream facilities with low duty factor beam. At the linac, the beam was accelerated to 181 MeV on the 10th of December, and then the beam was injected to the RCS on the 17th. At the RCS the beam energy reached to 3 GeV on the 20th. The beams were extracted to the MLF successfully and also to the MR on the 22nd. On that day, the acceleration to 30 GeV in the MR was achieved. And eventually, the beam was extracted to the neutrino area on December 24 and all the tuning work was safely completed on time on December 27.

We successfully accelerated the beam current almost the same as before the earthquake: the peak current of 15 mA and the pulse length of 500 μs at the linac, while the repletion was lower.

At the beginning of January 2012, we started beam tuning at the full repetition of 25 Hz at the linac and the RCS. During the tuning, we conducted the 300 kW test from the RCS (the corresponding linac power was 18.1 kW) and confirmed that we could increase the power when the neutron target was ready. In February, the beam current from the linac was increased from 15 to 20 mA and a 420 kW tuning with the RCS was carried out. When we tested this condition, we examined the effect of the misalignment of the RCS magnets due to the earthquake. It appeared that, by adjusting the operating parameters of the RCS, we could reduce beam loss in the RCS and also in the downstream beam transport line. Although the beam loss was still higher than that before the earthquake, the loss-amount was reasonably agreed with that from simulations and was at an acceptable level. Therefore, we decided to perform the realignment of the RCS magnets, which will take several months, in the summer of 2013.

Figure 4 shows the beam power history for MLF. We started user operation to the MLF on January 24 at the RCS power of 120 kW (the linac power of 7.2 kW), then increased the power as it was before the earthquake of 220 kW (the linac power of 13.3 kW) on March 15. In the last three days of the run before the summer shutdown, the stable operation of 275 kW at 3GeV (the linac power of 16.6 kW) was successfully demonstrated. Based on this result, we are going to increase the power to 300 kW from this fall.

Regarding the MR fast extraction, we started beam delivery at about 100 kW in January. As a result of faster repetition operation and parameter tunings, beam power to the neutrino increased from 160 to 200 kW while it had been 145 kW before the earthquake. Regarding the MR slow extraction to hadron users, we delivered the beam at 3 kW as it was before the earthquake in February, and increased to 6 kW in June.

The J-PARC accelerator facilities had been operating successfully until March 22, however, the operation stopped due to the trouble of the linac klystron power supply. This trouble was caused by the diode breakdown in the high voltage transformation unit. We first suspected that a cause of this trouble might have been also related to the earthquake damage or the following poor atmospheric condition. However, it was turned out that an underlying cause would be electrical damages that accumulated during the long-years operation. We could not recover the operation time anymore because the trouble occurred in

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March, at the end of fiscal year. As a consequence, the availability to users was down to 73% for JFY2011.

The user operation time of JFY 2012 (April 2012 - March 2013) is about 200 days. After resuming the beam operation from the klystron power supply trouble, we did not have any big troubles, and ended user operation in the morning of July 2 as scheduled. The total operating hours so far (from April 5 to July 2) are 2,104 hours. The deliverable beam times to the MLF, NU and HD were 1,646, 1058 and 376 hours, respectively, and the availabilities were approximately 94%, 90% and 94%, respectively.

The performance of the J-PARC accelerators is similar to or even better than before the earthquake in terms of beam power and availability.

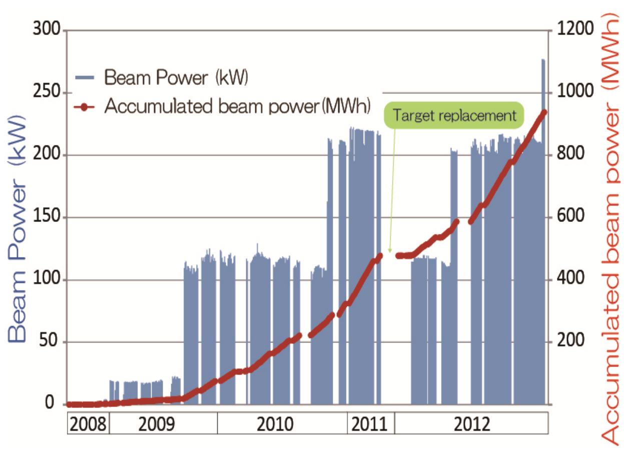

Figure 4: Beam power and accumulated beam power for the MLF users.

ISSUES OF THE LINAC IN BEAM OPERATON

The following two issues have been revealed in the beam operation after the earthquake: (1) the beam loss level became higher; (2) one of SDTL cavity units did not work at design RF amplitude. Beam loss mitigation is discussed in elsewhere[7].

There was a recognizable beam loss after the beam restoration, in particular after the SDTL straight beam transport section. Through a beam study, we found that beam loss was affected by beam trajectory, and to reduce beam losses, we had to adjust the beam trajectories at +5 mm and -5 mm as shown in Fig. 5. We found that high radiation dose points existed at vacuum pump boxes in the transport line, and there was a larger displacement than expected[8] as shown in Fig. 6.

After realignment of the boxes and ducts, the amount of beam loss declined to that before the earthquake. Through this problem, we learnt that we should have considered not only precise alignment of magnets and cavities, but also that of the other components, such as the ducts and vacuum boxes.

The second issue is on the SDTL section. One of the SDTL units, No.5, does not work properly within the designed RF amplitude region after the restoration. Therefore, we operate the SDTL at higher amplitude that is 109-116% of the designed value.

We tried to investigate a cause of this issue. Many peaks of hydrocarbon components in origin (e.g. mass of 12, 28, 44, etc.) are observed in the Q-mass data. We suspect if the cause is multipacting by hydrocarbons.

Before the earthquake, we used only ion pumps for the routine operation and we had seldom problems. But during the restoration, we purged the vacuum condition several times, and to recover the vacuum we used the rough vacuum system including an oil rotary pump. We suspect if oil vapor might have got back into the cavities. Therefore, we have already replaced oil rotary pumps with oil-free ones in the summer shutdown of 2012.

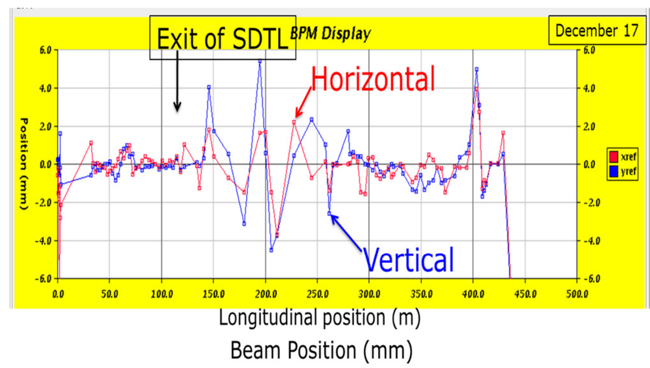

Figure 5: Beam position at the minimum beam loss condition on December 17, 2011.

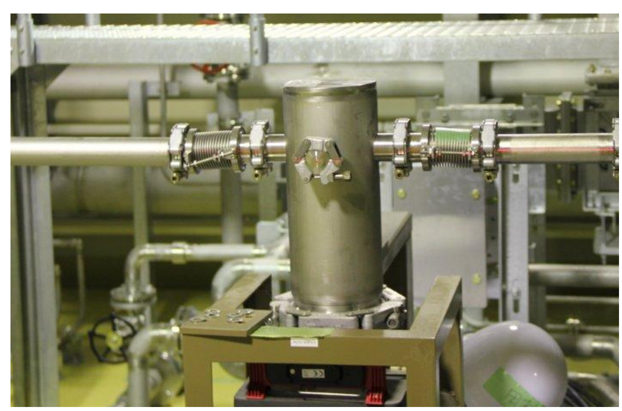

Figure 6: Displacement of the box. Deformed bellows with a red laser level marker line are shown.

LESSONS LEARNT FROM THE EARTHQUAKE

We have many learnt lessons from the earthquake.

Earthquake Proof System

An earthquake proof system is equipped to the DTL and SDTL tank support[9]. The system gives flexibility to the movement in X- and Z-axes. Thanks to the system, we thought, we didn't have significant displacement of the drift tubes. A mechanical flexibility (in the range of 25 mm) helped to avoid having DT displacement. But bellows and monitors between the cavities could not stand for these flexibilities and broken. In this case, because the time of "DT realignment" is much longer than the time of "bellows and monitor rebuild", the earthquake proof system contributed to short restoration time. Through this problem, we learnt that we should consider side effects in advance to mitigate the total damage.

Also we had to clear in the movable area to secure the earthquake proof system. But we can see some materials such as a bolt, a hose or a cable, after the earthquake. The reason why that we did not investigate this area was because we assumed that we would not have big earthquakes like as the 3.11 earthquake in the near future. To cope with the disasters, we have to recall the famous Japanese saying "A natural disaster will happen when we least expect it." (by Dr. Torahiko Terada, physicist, 1878-1935).

High Humidity

Because the air conditioning system was broken and not available for several months, we used several dehumidifiers in the tunnel during the restoration work. But we could not maintain the normal humidity for instruments, and had to leave them under a very high humidity (> 70 %) condition. This caused many troubles such as a discharge at ion pump connectors, bad electricity connection and poor insulation, etc., even after the beam operation. Lessons Learnt: We should keep off high humidity. (We know, but in realistic, it is not easy to maintain low humidity because the volume of the tunnel is huge for several small dehumidifiers.)

Loose Connection of Coaxial Line

After the user operation, we had troubles several times due to a loose connection of coaxial lines, WX-203D. Although we checked the connection or tighten screws during the restoration, the screws became loose. We found that these troubles were caused by frequent aftershocks. We had no spring mechanisms in the screw. Lessons Learnt: We should consider occasional movement of aftershocks in mechanical design.

FUTURE SCOPE OF LINAC

The full energy (400 MeV) linac is necessary for the J-PARC facility to reach the nominal performance of 1 MW at RCS and 0.75 MW at MR. For beam energy upgrade from 181 to 400 MeV, we plan to install a new accelerating structure ACS (Annular-ring Coupled Structure)[10] and a 400 MeV RCS injection system. And also we need to upgrade the peak beam current from 30 to 50 mA. The development of new ion source[11] and RFQ[12,13] are underway.

Due to the users request to run fully during JFY2012, the installation of 400 MeV linac is postponed from 2012 to summer of 2013. After the installation and beam tuning, we will ramp up the beam power towards 1 MW at 3 GeV.

SUMMARY

J-PARC had severe damage by the earthquake, but it has been fixed in 9 months. User operation was resumed in January 2012. But some repairs are still temporal and permanent measure is needed. We are still working to recover from the damage.

The performance of the J-PARC accelerators is good as before the earthquake or better than before in terms of the beam power and the availability. Users accumulate data and many fruitful results are published.

Regarding the linac performance upgrade, the construction of the 200-400 MeV linac and the development of higher current ion source and RFQ are underway. They will be installed in summer 2013 and we will ramp up the beam power.

We have many lessons learnt from the earthquake. Some of them are trivial and/or specific to the earthquake. But in case of disaster, I would like to emphasize that not only the hardware preparation, but also software-like preparation such as "occasional evacuation drill" is quite important.

We didn't expect tsunami before the earthquake. Now we have in mind of the height above the sea level, and we prepared gears to save our lives.

We don't hope big earthquakes again, but next time, we could be able to manage better.

In the remark, we received encouragement, offers, donations, support, etc. from the world after the earthquake. We deeply appreciate your kindness and support that we received from all over the world.

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