J-PARC Accelerator Status

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Abstract

Japan Proton Accelerator Research Complex (J-PARC) has started the beam delivery at 2009 to the experimental facilities which are the neutrino experimental facility (T2K), the hadron experimental facility and the material and life science facility (MLF). However J-PARC had two big troubles during last three years: First one was induced by the Great East Japan Earthquake happened in March 2011 and the second one was caused by the radioactive material leakage from hadron experimental facility in May 2013. The damage to the accelerators from both troubles has been fixed by the effort of members. As a result J-PARC has resumed the beam delivery to users. The achieved beam power for T2K is 240 kW which is one third of design value of 750 kW. In this report, the status of the accelerator operation of J-PARC is described. Furthermore it is also described the measurement of the extinction level for the physics experiment.

Keywords: Proton accelerator, Intensity frontier, T2K, Neutrino, COMET, Muon

1. Introduction to J-PARC

Japan Proton Accelerator Research Complex (J-PARC) constructed by the collaboration between KEK and Japan Atomic Energy Agency (JAESA) is a high-intensity proton accelerator facility. It is in the Tokai campus of JAESA by the Pacific Ocean as shown in Fig. 1.

The construction of the J-PARC began at 2001 and it was completed at 2007. The first beam commissioning of the accelerators was carried out during the period from 2007 to 2009. From 2009 the beam delivery to users was started.

The accelerator of J-PARC consists of a 400 MeV linac, a 3 GeV rapid cycle synchrotron (RCS) and a 30 GeV main ring synchrotron (MR). J-PARC has three experimental facilities. These are the Material and Life science Facility (MLF), Neutrino experimental facility (T2K) and Hadron experimental facility, respectively. Furthermore J-PARC has started the design of the test facility for the accelerator-driven transmutation system.

J-PARC began the beam extraction to the neutrino experiment (T2K) and the hadron experiments at 2009. However J-PARC had two big troubles during last three years. First one is the Great East Japan Earthquake happened in March, 2011. It was required 9 months to fix the damage by the earthquake. The second one is the incident of the radioactive material leakage from the hadron experimental facility in May 2013. Damages and causes of the incident has been fixed by the reconstruction of system of J-PARC center except for the Hadron experimental facility. Therefore J-PARC was able to resume the beam delivery to T2K and MLF. Hadron facility is required to redesign the facility includes the beam target. Thus the restart of experiments may be in February 2015 at the soonest.

The achieved beam power for T2K is 240 kW which is one third of design value of 750 kW. Just before the incident, the beam power for the hadron experiments was 25 kW which is one fourth of design power of 100 kW.
2. Facilities

As mentioned in the introduction, J-PARC has three facilities. The outline of them are described in the following sections.

2.1. Material and Life science Facility (MLF)

MLF shown in Fig. 1 supplies users with the strong neutron and muon beam which are made by the intense 3 GeV proton beam from the RCS. MLF has 21 neutron beam lines and four muon beam lines. The target for the muon production is located in the upper stream of the neutron production mercury target.

The beam power on MLF target is 300 kW for the practical operation at present time. The achieved power in RCS in the beam study is approximately 0.6 MW which is just 60% of the design beam power of 1 MW. However the beam study to achieve the 1 MW on MLF target will be started because the linac beam energy and beam current has been upgraded.

2.2. Neutrino experimental facility

The neutrino beam is produced by the intense 30 GeV proton beam extracted from MR. The extraction beam line for the neutrino target is located inside of the ring. Thus it requires the stronger magnetic field so that the neutrino beam line uses the superconducting combined magnet shown in Fig. 3.

2.3. Hadron experimental facility

The main experiments in the hadron facility are nuclear physics with kaon. Recently the electron-muon conversion experiment called COMET[7] has been approved. Therefore the new beam line for the COMET is being constructed. Unfortunately the incident of the radioactive material leakage upset the schedule of the experiment in the hadron facility. For the prevention of recurrence of the incident, the facility shown in Fig. 4 is being reconstructed. In particular, the airtightness of
the target chamber and the following beam line must be kept in the new facility.

Figure 4: Hadron experimental facility before the incident. Reconstruction of the facility is on going.

3. Accelerators

J-PARC consists of 40 MeV Linac, 3 GeV RCS and 30 GeV MR[1]. Special futures of each of accelerators are explained in the following section.

3.1. 400 MeV Linac

The 400 MeV injection linac comprises of the an H⁻ ion source, an RFQ linac, DTLs, separated type DTLs (SDTLs) and annular-ring coupled structure (ACS) linacs. The resonant frequency of cavities except for ACS linac is 324 MHz. That of the ACS is 972 MHz. Total length of the linac is approximately 240 m.

SDTL has been originally developed for the future intense proton linac project in KEK called Japanese Hadron Facility (JHF)[2]. The ACS linac was added to SDTL at the end of 2013[4] in order to increase the beam energy from 181 MeV to 400 MeV. The ACS has also been developed originally in KEK[3]. However the resonant frequency of the original ACS was 1296 MHz. Thus ACS for J-PARC was redesigned to adjust the frequency[5]. One ACS module of J-PARC shown in Fig. 5 is composed of two accelerating tanks which are coupled by the bridge cavity.

The repetition rate of the linac is 25 Hz and the pulse length of the beam is 500 μs. The peak current of the beam was 15 mA for the practical operation. However the ion source and the RFQ were replaced in order to accelerate the beam of 50 mA during the summer shut down of 2014. Thus 50 mA beam acceleration will be tried from autumn of 2014.

Figure 5: An ACS module for J-PARC linac.

3.2. 3 GeV Rapid Cycle Synchrotron

The repetition rate of the RCS is also 25 Hz in order to accept the all beam from the linac. The schematic view of the RCS is shown in Fig. 6. The diameter of the ring is approximately 100 m. RCS ring comprises three straight sections and three arc sections. The straight sections are used for the injection of 400 MeV beam from the linac, the extraction of the 3 GeV beam to MLF and MR and the beam acceleration with RF cavities respectively.

The beam ducts of the RCS are made of the ceramics in order to avoid the effect of the eddy current induced by the rapidly changing magnetic field. Furthermore the outer surface of the ceramic duct is covered by the narrow conductive lines made of the plated copper along the beam direction. Radiation by the circulating beam in RCS is confined in the duct by the copper lines.

The transition energy of the RCS is 9.14 GeV which is greater than the maximum energy of RCS. Thus RCS has no transition which makes a serious beam loss. The RF harmonics of RCS is two and bunch number is also two.

Figure 6: Schematic view and parameters of RCS.
Almost beam accelerated in RCS is delivered to MLF. History of delivered beam power on the target of MLF is shown in Fig. 7. The beam power is gradually increasing. Although the designed beam power is 1 MW, the beam power of the practical operation is 300 kW at present. However approximately 0.6 MW has been achieved in the beam study. On this October, it will be tried to accelerate the 1 MW beam because the upgrade of linac was done as mentioned before.

![Figure 7: History of beam power on MLF target](image)

**3.3. 30 GeV Main Ring synchrotron**

A part of 3 GeV beam from RCS is injected into MR. The shape of the MR is similar to the RCS as shown in Fig. 8. It has three straight and arc sections. However the diameter of the ring is approximately 500 m which is 5 time of that of the RCS. The most important feature of the MR is that the momentum compaction factor of the MR is negative which is realized by the missing bending magnet scheme. As the result, the transition gamma become an imaginary value so that the MR has no transition energy.

MR has two operation modes which have the deferent repetition rates. These are the fast extraction (FX) mode with the repetition rate of 2.48 s and the slow extraction (SX) mode with that of 6.00 s. The FX mode is used for the neutrino experiment and the SX mode is for the hadron experiment. While all beam in MR is extracted to the neutrino beam line just after the acceleration in the FX mode, the beam is kept in the ring after the acceleration and it is gradually extracted to the hadron beam line in the SX mode.

Fig. 9 is the history of beam power delivered to the target of T2K neutrino experiment. Although the design beam power is 750kW, the achieved power is 240kW. Thus the almost equipments of MR is being improved gradually in order to achieve the design beam power.

The R&D status of RF cavity is discussed in the following section as an example.

![Figure 8: Schematic view of MR.](image)

![Figure 9: History of beam power on T2K target](image)

For the SX mode, uniformity of the extracted beam intensity is important to keep the event rate constant. Furthermore the beam extraction efficiency must be high to decrease the radiation level of the equipments. The extraction efficiency is 99.5% at the present time. It is high enough for the present beam power level.

The uniformity is represented by duty factor of the beam spill defined by the following equation:

\[
Duty \text{factor} = \frac{\left( \int_0^T I dt \right)^2}{\int_0^T dt \int_0^T I^2 dt}
\]

The duty factor of the beam spill shown in Fig 10 is 43%. Although this data was observed with beam power of 15kW, the duty factor was not changed when the beam power was increased to 25kW. However it is required to increase the duty factor more by the improvement of magnet power supplies because the spike signals in the extracted beam intensity distribution are mainly due to the ripple of the output current for the main magnets.
4. Upgrade plan of the accelerators

Original upgrade plan of MR in order to achieve the beam power of 750 kW was to increase the beam energy from 30 GeV to 50 GeV. However the plan has been modified from the energy upgrade to the increment of the repetition rate of beam. The designed beam power is not changed. The reasons of this modification of the plan are as follows:

1. Beam power takes precedence over beam energy.
2. No strong requirement for 50 GeV beam from users.
3. Increment of electricity charge must be suppressed:
   The electricity charge of 50 GeV operation of MR requires approximately four times larger than that of 30 GeV operation because of the saturation of the magnets.

For FX mode, the repetition rate is 2.48 s at present. It must be reduced to less than 1.3 s. Thus many equipments of MR must be modified or replaced to achieve higher repetition rate until JFY2017. For instance, new RF cavity developed recently has nearly twice as much voltage for the beam acceleration as the present one because the acceleration period become half of the present one.

4.1. RF cavity of rings

The new RF cavity in the MR, which has the double accelerating voltage compared to the present cavity, was realized by using the special material called the FINEMET FT-3L[6]. Present RF cavities in RCS and MR of J-PARC use the magnetic material FINEMET FT-3M. FT3L is one of the FINEMET which is annealed under the magnetic field in order to align the magnetized axis. As the result, the impedance of the RF cavity is doubled. First RF cavity with the core made of FT3L FINEMET was produced and tested in the high-power test bench as shown in Fig. 11. It will be install in the tunnel for the practical use during the summer shutdown period.

5. Recent research for the physics experiment

Last topic is the recent result of the accelerator study for COMET experiment[7]. COMET is the muon to electron direct conversion search experiment. It requires extremely small value for the extinction level. Extinction is defined as a residual to primary ratio of beam intensity. Since the extremely small extinction level has been achieved by the chopper of linac and the beam injection kicker of MR, it is reported in the following sections.

5.1. Extinction for the RF chopper of linac

Linac beam pulse which is 500μs in length is chopped by the chopper in order to eliminate the beam which RCS RF bucket can not accept. The bunches in the rings are shown in Fig. 12. The region among the bunches must be empty. Thus the copper in linac is required to eliminate the unwanted beam.

Figure 10: Example of the beam spill time structure

Figure 11: High-power test of FT3L 5gap cavity.

Figure 12: Bunch scheme in rings of J-PARC.
The chopped-beam time structure is shown in Fig. 13. The chopper is installed in the beam transport line between the RFQ and DTL. The chopper is an RF deflector as shown in the left photo of Fig. 14. The right data Fig. 14 is the output signal from the current transformer. Top 3 lines show the beam current before chopper. Bottom one shows the beam current after chopper. The ratio of current in the chopped region to top value of the current defines the extinction level.

![Figure 13: Chopped beam time structure.](image1)

Extinction level achieved by the chopper has been estimated by the measurement of neutron production rate on the mercury target in MLF. By comparison the neutron production count between the full chopped beam and common chopped beam, the extinction level of $10^{-7}$ for RCS was fixed. It is significantly small value for the accelerator. However it is too large for COMET experiment.

5.2. Extinction in MR for COMET

Then cleaning up the almost empty bunch in RCS is done by the following idea. Usually two bunches are injected at same time in the MR from RCS. In this case the injection kicker magnet works in the timing as shown in top small figure in the ring shown in Fig. 15. In this case, both bunches from RCS are injected into MR even if one of them is almost empty. Then the kicker timing was delayed a half of period as shown by the bottom small figure in the ring of Fig. 15. As the result, the empty bunch can not enter the MR. Furthermore the voltage of RF bucket was tuned to suppress the leakage of beam from the RF bucket. This experiment has been carried out with 8GeV beam with one bunch and beam power was approximately 3.2kW.

Measurement was done using the abort dump line. The preliminary result shows that the extinction level is about $10^{-12}$. It is enough to suppress the background for the COMET experiment of the first phase[8].

![Figure 14: Chopper cavity and beam current.](image2)

6. Summary

The short summary of this report is given below.

1. J-PARC are delivering the 300 kW proton beam to MLF, the 240 kW beam to T2K and the 25 kW beam to the hadron facility.
2. Achieved values of beam power on targets are still smaller than the design values.
3. Since the energy and beam current of the linac have been upgraded, it is possible to study the 1 MW beam acceleration by RCS.
4. Design beam power of 750kW for MR will be achieved by modification or replacing the equipments of MR until JFY2017.
5. Beam study for COMET experiment is being continued. The very small extinction level has been observed.

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