J-PARC STATUS

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Abstract

The Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose facility making full use of secondary particles like neutrons, muons, Kaons, and neutrinos produced by the MW-class proton accelerators. The J-PARC accelerator scheme inserts the 3-GeV Rapid-Cycling Synchrotron (RCS) in between a 400-MeV injector linac (at present 181 MeV) and a several-ten GeV Main Ring (MR). The RCS has already demonstrated extraction of one pulse of 2.6×10^{13} protons at 3 GeV, which corresponds to 310 kW if operated at 25 Hz, with a beam loss less than one percent, and a beam power of 210 kW for a period of 70 sec. The MR beam acceleration has been done on December 23rd, 2008. Also, the neutron production target was beam-commissioned, providing high-resolution, high-efficiency neutrons. The Hadron Facility and the Neutrino Facility have been beam-commissioned in January and April, 2009, respectively. Rationale for the J-PARC accelerator scheme will be resumed on the basis of the results and difficulties encountered during the development, the construction and the commissioning.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) [1-15] Project is a multi-purpose one to promote a wide variety of scientific fields, making use full of the secondary beams generated by the high-intensity, high-energy proton beams. In particular, neutrons and muons are used for materials and life science, kaons for both kaon rare decay experiments and hypernuclei experiments, and neutrinos for long-base line neutrino experiment. Industrial application has also started, while the basic study for the Accelerator-Driven Nuclear Waste Transmutation System (ADS) has been shifted to the Phase II.

In general, the number of the secondary beams is proportional to the beam power, if the beam energy exceeds the threshold of their productions. In order to provide many kinds of users with the appropriate high-power beams, the 3-GeV, 1-MW Rapid-Cycling Synchrotron (RCS) is placed in between the 400-MeV injector linac and 50-GeV Main Ring (MR), and is used to produce the pulsed neutrons and muons at the Materials and Life science experimental Facility (MLF) as shown in Fig. 1. It may be said that this accelerator scheme is one version of KEK PS, upgraded by approximately an order of magnitude in both their beam energies and beam currents (the KEK PS comprised a 40-MeV linac, a 500-MeV RCS and a 12-GeV MR). The distinctive features of the J-PARC accelerator mostly arise from this multi-purpose concept as detailed in the next section.

Another aspect of the J-PARC project is that the project started, joining the Japan Hadron Facility (JHF) project and Neutron Science Project (NSP), respectively promoted by High Energy Accelerator Research Organization (KEK) and former Japan Atomic Energy Research Institute (JAERI), which was put together with Japan Nuclear Cycle Development Institute (JNC) to form present Japan Atomic Energy Agency (JAEA).

The accelerator construction, which officially started in 2001, went on schedule, while the beam commissioning of all the three accelerators and the three facilities started on schedule as well (the schedule was fixed in 2005). More specifically, the linac and RCS succeeded in beam acceleration a few months ahead schedule, on January 24th, and on October 31st, 2007, respectively. Finally, the MR beam was accelerated to 30 GeV (the first goal) on December 23rd, 2008, again as scheduled. The RCS beam was extracted to the spallation neutron source on May 30th, 2008, the muons were produced on September 29th, the user run for the neutron experiments started on December 23rd, and the MR beam was extracted to the Hadron Experimental Facility on January 27th, 2009. Finally, the fast extraction to the neutrino production target was done on April 23rd.

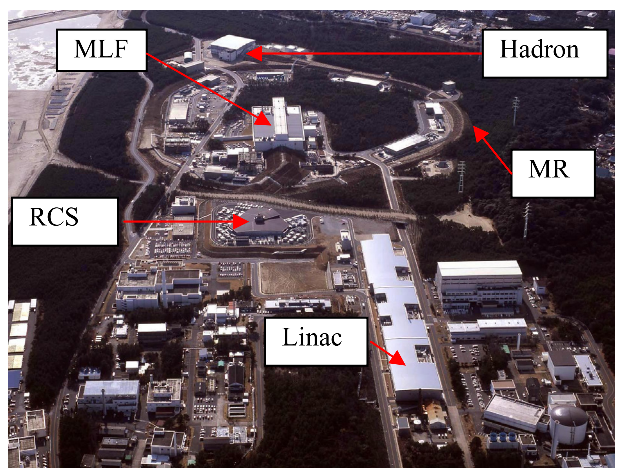

Figure 1: The bird-view photograph of the J-PARC site.

One pulse of the RCS beam, which would provide a beam power of 310 kW, if operated at a design repetition of 25 Hz, was injected, accelerated and extracted with a beam loss less than 1 percent, which is far below the designed tolerance. This makes it promising by a scaling law of $\beta^2\gamma^3$ of the space charge effect that the J-PARC RCS will be able to provide a beam power of 1 MW, if injected at an energy of 400 MeV. The construction of the high energy linac has just started to upgrade the linac beam energy from the present 181 MeV to 400 MeV at the end of March, 2009. Since the qualities of the neutron beams generated by the J-PARC neutron target have already demonstrated its excellent performance in both the neutron intensities and the energy resolutions, the J-PARC could be the world-class neutron facility by this upgrade.

However, we still need big efforts to improve a number of the accelerator components. In particular, both the RFQ linac and the ring RF system require quick action to develop their robust back-up versions in order to meet the users' urgent requests. In this report, distinctive features of the J-PARC accelerator will be presented together with the results of the developments for realizing these features, and then the beam commissioning results will follow. The J-PARC MR status detailed in the other invited paper [16] will be briefly reported here.

DISTINCTIVE FEATURES OF THE J-PARC ACCELERATOR

As mentioned in the previous section, the multi-purpose is a key word for specifying the J-PARC, which is to generate both the proton beams with an energy of several ten GeV and those with an energy of a few GeV. The former should be extracted either fast or slowly with a beam power of 0.75 MW, depending upon the experimental requirements. The latter should be fast extracted with a beam power of 1 MW, a pulse length shorter than 1 μs, and a repetition rate of around 25 Hz for the spallation neutron source. The J-PARC needs an RCS as an efficient injector to the MR, while the RCS can be used as a pulsed neutron source (and a muon, too). This is the first reason why the J-PARC chose the RCS scheme rather than the Accumulator Ring (AR) scheme with a full-energy linac such as SNS and LANSCE. The second reason is that the RCS-based neutron source may be more advantageous over the AR-based one, since the beam current of the RCS can be lower than the AR with the same beam power, if the RCS energy is higher than the AR energy. Moreover, the beam loss inherent to the beam injection is more tolerated in the RCS than the AR, regarding both the load on the beam collimator and the residual radioacitivity, since the beam injection energy to the RCS can be lower than the AR. The pros and cons for RCS versus AR were detailed in the previous publication [15] and references therein.

The conclusion of the discussion is very much dependent upon how technically difficult the rapid acceleration is. Among all, it is most vital to the RCS scheme that any beam loss is eliminated during or after the acceleration, since the beam loss after some acceleration gives rise to the significant radioactivity. However, the normal FODO lattice implies that the beam has to pass the transition energy during the course of acceleration. At that energy, where the restoring force for the phase oscillation vanishes, the phase stability is lost, resulting in the beam loss. In order to avoid the transition, the beam optics of the RCS and MR have been designed on the basis of the high-γ_T lattice and the imaginary-γ_T one, respectively, by using the missing bend technique. In other words, the transition energy of 9 GeV of the former is higher than the final acceleration energy, while the latter has no transition energy. The beam commissioning results will be detailed in the following section. In addition to the beam optics design the RCS should have the following features.

First, the rapid acceleration requires the high-field gradient RF accelerating system. Second, the rapid acceleration requires the rapid ramping of the magnetic field, which would have induced the eddy current on the metallic surface. In order to suppress the eddy current, ceramics vacuum chambers should be used with RF shielding, while the magnetic coils should be stranded. Third, the lower injection energy in turn implies higher space charge effect. In order to mitigate the effect the large aperture magnets as shown are required, giving rise to large fringing fields. Also, the beam is difficult to uniformly inject into the large aperture together with the charge exchange through a foil and its extraction is hard to manage, too. These challenging developments and the mass production of these components are reported in the following sections.

MAGNET ALLOY (MA) LOADED CAVITY

The rapid acceleration requires the high accelerating field gradient. Since the J-PARC 3-GeV RCS (25 Hz, 0.18 to 3 GeV) accelerates the beam twice as fast as the ISIS RCS (50 Hz, 70 to 800 MeV), which was the world rapidest so far, it needs the field of 23 kV/m which is twice as high as those for the conventional ring RF systems. Here, the missing bend lattice, requiring longer arc sections than those of the conventional FODO lattice, shortens the straight sections available for the RF acceleration. It is here noted that the circumference of the RCS for the pulsed neutron source is quite limited by its short pulse length. This high field gradient at the accelerating gap can be generated only by the high RF magnetic flux density in the magnetic core. The ferrite, which has been conventionally used in proton synchrotrons, cannot stand the RF magnetic flux density, which is necessary typically beyond a field gradient of 10 kV/m. On the other hand, the higher field gradient is potentially feasible by using the magnetic alloy (MA) core, since the μQf value of the MA core has almost flat response to the magnetic flux density, which generates the electric field gradient up to an order of 100 kV/m (the μQf value is proportional to the shunt impedance).

The MA-loaded cavity has another advantage over the conventional ferrite-loaded ones. Since the Q value can be extremely low (a value of less than one is possible), no tuning system is necessary. Also, the second-harmonics of the RF power can be provided into the accelerating cavity. On the other hand, its high R/Q (low stored energy) with the low Q value requires the wide-band beam loading compensation via feed-forward control. As a result, even the high power system should be wide-band.

In order to minimize the band width necessary for the compensation, the Q-value is optimized by adjusting the gap between the MA cores radially cut under the condition of no tuning system. The Q values thus optimized are 2.9 (1.5-mm gap) [2 (1-mm gap) for 180-MeV injection] and 10 (10-mm gap) for the RCS and the MR, respectively.

The cross-sectional surface of the cut cores, however, was seriously damaged under the high RF power loading. During the course of the development, it was proposed that both the Q value and the resonant frequency of the RCS cavity with uncut cores can be adjusted by adding the inductance in parallel to the cavity. However, even the uncut cores were damaged by the transverse electric field on the MA cores near the acceleration gap. It was found that the electric field, thus the current by this, melted the rare shorts between the MA layers, giving rise to catastrophically disastrous results. The MA layers should be insulated by the thin (2 μm, typically) silica layer in between. The rare shorts arose from scratching the silica insulator during the process of winding the MA tapes to form the cores. We could finally solve this problem, improving the manufacturing process in the factory.

The MR RF system is such that both the Q value and resonant frequency of the MR system are higher than those of RCS system. Thus, any value of the added inductance could not meet both the high Q value and the high resonant frequency, simultaneously. Therefore, we had to continue the development of the cutting technique of the MA cores for the MR system. We have finally developed the cut cores, which can stand the designed power load, incorporating the above improvement in the MA core insulation and the diamond polishing of the cut surface.

Both the uncut cores for the RCS and the cut cores for the MR had been well in operation typically beyond 2,000 hours, contributing to the successful beam commissioning of both the RCS and MR. However, it was found after 3,000-hour high-power RF operation that one of the eleven RF cavity systems in the RCS revealed the degradation in its impedance. In the J-PARC ring RF system, one RF cavity system being driven by one power amplifier comprises three accelerating gaps, each of which is loaded with six cores. The core, which revealed the low impedance, was mechanically crushed perhaps by the heat cycling. Further worse is that the other five cores, the impedances of which have indicated no degradation yet, more or less showed slight symptoms of this kind of mechanical crushes. Although this problem does not have any bad influence on the beam operation for the time being, the development of more robust cores is definitely necessary. In parallel to the beam operation, we need a ceaseless effort to improve the MA cores.

TECHINICAL ISSUES IN RCS OTHER THAN RF

Ceramics Vacuum Chambers

All the vacuum chambers of the RCS exposed to the fast varying magnetic fields have been made of the alumina ceramics. Those for the quadrupole magnets (QM's) have the circular cross section, which is relatively easy to manufacture. On the other hand, the cross section of the race-track shape was chosen for the bending magnets (BM's) in order to keep the large physical aperture with the reasonable cost.

For the injection section, the special shapes of vacuum chambers were needed. Much longer time than expected is required for the development and/or the mass production of these ceramics vacuum chambers, in particular, with the special shapes. Some chambers were delivered to the J-PARC site just in time.

Large Aperture Magnets

In order to mitigate the space-charge defocusing effect, the QM's should have the large aperture, being short and close to the neighbouring one for the frequent focusing. Then, the fringing field is quite strong, also being significantly interfered with those of the neighbouring QM's. Together with the saturation effects at the core ends, large higher multi-pole components might substantially reduce the dynamic aperture. If this were to happen, octa-pole magnets should have been installed to recover the dynamic aperture. Fortunately, the dynamic aperture is sufficiently large in the beam simulation, which took into account the measured data for the actual magnet layouts..

Magnetic Field Tracking

From the beginning, it was expected that the electromagnetic compatibility issue is very difficult to solve for the RCS magnet system. For this reason, it was scheduled to use one year for powering and controlling test of the magnet system in-situ. The QM's are driven by seven parallel-resonant circuit networks, while the BM's are driven by a single series-resonant one. The IGBT-based power supplies are used, since the fast switching of the IGBT is required for the precise tracking of all the magnetic fields. However, the fast switching implies the high-frequency components, which can be easily coupled between the other networks through the incomplete grounding. In fact, some chassis or some grounds revealed several hundred volts at some frequency components. Although almost all the electromagnetic compatibility issues have been solved, that for the shift-bump system still remains unsolved. The in-situ efforts were also exerted to improve the signal-to-noise ratios of almost all the beam diagnostics systems, by means of filtering the noises in addition to improving the electromagnetic compatibility.

Injection and Extraction

The injection and extraction devices for the large aperture of the beams are difficult to develop and manufacture. In particular, the decay of the magnetic fields of the injection bump magnets should be faster than 100 μs for the beam power of 1 MW. This is required for reducing the number of hitting of the circulating beams on the charge-exchange foil. The capacitors installed to the ceramics vacuum chamber, through which the mirror current of the beam passes, were damaged by this fast switching noise. Right now, the capacitors are removed, while the field decay time is relaxed to 250 μs. In near future, the present capacitors (250-V specification) will be replaced by more robust ones (1.2-kV specification).

LINAC

Our effort has been concentrated on building the high-quality linac, since the low-emittance beams should be stably delivered to the RCS. In particular, the stability of the beam energy is most important. For this purpose, the linac scheme was chosen as follows.

The H^- ions produced by the volume-production type of ion source are guided through the 50-keV Low Energy Beam Transport (LEBT) to the 3-MeV, 324-MHz Radio-Frequency Quadrupole (RFQ) linac. Then, the beam is transported via the 3-MeV Medium Energy Beam Transport (MEBT), where a 324-MHz RF chopper and bunchers are installed, to the 50-MeV, 324-MHz Drift-Tube Linac (DTL). Finally, the 324-MHz Separated DTL (SDTL) and the 972-MHz Annular-Ring Coupled Structure (ACS) linac accelerate the beam to 191 MeV and 400 MeV, respectively. The ratio of the accelerating frequencies is of odd number in order to keep the possibility of simultaneously accelerating both the protons and the H^- ions for future use.

It is preferable to choose the higher accelerating frequency for overcoming the space charge force of the high-intensity proton linac, since the focusing period is shorter both longitudinally and transversely. Furthermore, one can use klystrons which are most stable and reliable RF power sources. On the other hand, it is also important to keep the flexible knob for the transverse focusing by means of electro-quadrupole magnet (EQM) system rather than permanent one. However, EQM's with water cooling channels are difficult to produce for small space which is allowed for the high-frequency acceleration. In order to meet these two conflicting requirements by producing the smallest-possible EQM's we have made full use of the electroforming technique together with wire cutting. The DTL frequency of 324 MHz became thus feasible.

The MEBT design is another issue. One has to solve many conflicting requirements both mechanically and electromagnetically, installing choppers, bunchers, magnets, monitors and so forth in the limited space. The 3-MeV MEBT with the frequencies of 324-MHz for RFQ, DTL, bunchers and RF choppers were thus chosen. The π-mode Stabilizing Loop (PISL) was invented for realizing the 3-MeV, 324-MHz RFQ. The first RFQ stabilized by PISL had been manufactured at a frequency of 432 MHz, accelerating the proton beam to an energy of 3 MeV, which had been the world highest at that time.

The 324-MHz, 3-MW klystrons developed for the J-PARC DTL and RFQ have been in stable, reliable operation with a repetition of 50 Hz and a pulse length of 600 μs. For this reason, the frequency of 324 MHz and the MEBT energy of 3 MeV have been chosen for the future project. Here, the superconducting cavity technology is kept in mind for the future GeV-class superconducting proton linac. Since the frequency of 324 or 325 MHz is one quarter of the L band chosen by superconducing International Linear Collider (ILC), one can then have a full benefit from the world-wide ILC collaboration.

BEAM COMMISSIONING OF TRANSITION-FREE LATTICE WITH MA CAVITIES

As mentioned in the introduction, one pulse of 2.6×10^{13} protons, which corresponds to the beam power of 310 kW if operated at 25 Hz, was many times sent from the RCS to the neutron production target. Here, a peak current of 15 mA with a macro pulse length of 500 μs and a medium pulse length of 600 ns (chopped at MEBT) was delivered from the 181-MeV linac to the RCS. A beam loss of one percent is almost concentrated in the beam injection period as typically shown in Fig. 2 [17]. This fact indicates that the transition-free optics design is effective for suppressing the beam loss during the acceleration. Also, this new optics design has no unexpected significant harm on the high-intensity beam injection. It is noted that the Lasslette tune shift of – 0.16 at this injection is the same as that of the 1-MW RCS beam case with the 400-MeV beam injection to the RCS. It is noted that the scaling law by $\beta^2\gamma^3$ as revealed in the Lasslette tune shift can be used for the space-charge effect in general. Here, the beam was painted during the injection into an emittance of 150 π mm·mrad both horizontally and vertically. Also, the second-harmonics RF field of 80 percent as high as the fundamental one was applied to the beam together with the phase sweep of – 80 degrees to 0 degree. The momentum offset of – 0.1 percent was also used. It is here emphasized that the low-Q MA-loaded cavities can be excited by the second-harmonics RF power together with the fundamental one (no additional second-harmonics cavity is necessary). These RF gymnastics are detailed in Ref. [18], while the comparisons with the beam simulation results are presented in Ref. [17].

A slight beam loss at the high-dispersion section was still observed during the acceleration. This is perhaps because the sextupole magnets are excited only at the injection for the chromaticity compensation. It is expected that this slight beam loss can be eliminated by compensating the chromaticity during the acceleration.

It is also demonstrated that beam powers of 100 kW and 200 kW were extracted from the RCS for one hour and 7 sec, respectively. In this way, the beam commissioning had been very smoothly in progress until the end of September, 2008. As a matter of course, this is because all the accelerator components had been reliably and stably in operation. In particular, the linac operation had been very reliable and stable as an injector. The linac beam availability amounted to 90 percent until that time.

The measured emittances are listed in Tables 1 and 2. During the acceleration by the DTL the rms emittances significantly grew, while no halo formation was observed beyond the Gaussian charge distribution. On the other hand, the rms emittances negligibly grew throughout the SDTL acceleration, while some halo formation was observed. These are perhaps because the accurate matching has not yet been completed.

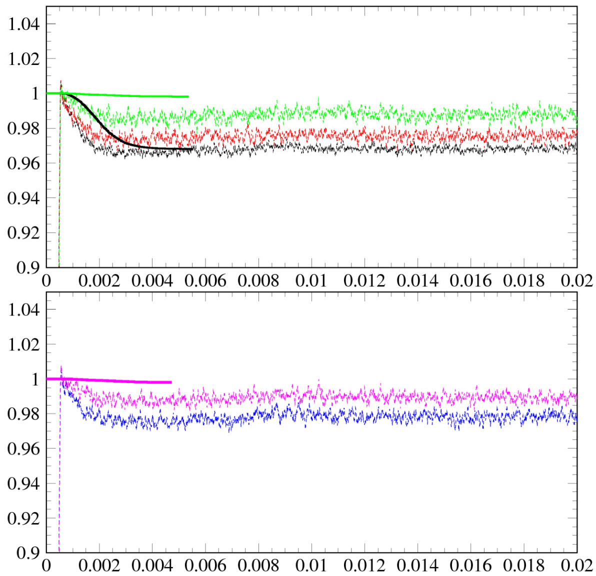

Figure 2: The survival rates [17] as measured by means of DCCT. The horizontal axis is the time duration in sec. The upper and lower ones are for beam pulses which are equivalent to 300 kW and 322 kW, respectively. The solid curves and dotted ones show the results of the beam simulations and the measurements, respectively. The pink ones are mentioned in the text. The black ones and red ones are for no longitudinal paintings and for 80 % second harmonics, respectively. Green ones and blue ones are for – 0.1 % momentum offset in addition.

Table 1: Beam Emittances of J-PARC Linac Measured by Means of Wire Scanners at a Peak Current of 5 mA (Normalized rms in π mm mrad)

	Horizontal	Vertical
MEBT [a)]	0.22	Not measured
DTL exit	0.27	0.25
SDTL exit	0.23	0.27
After the space for ACS	0.25	0.27

a) A double-slit emittance monitor was used.

Table 2: Emittances Measured at 30 mA

	Horizontal	Vertical
MEBT [a)]	0.22	Not measured
DTL exit	0.42	0.36 [a)]
SDTL exit	0.35	0.40
After the space for ACS	0.37	0.40
Designed	0.3	0.3

After the end of September, 2008, the discharge in the RFQ became the most serious issue regarding the J-PARC beam operation. For example, the unscheduled down time in May and June, 2008, is only 5.4 percent of total linac operation of 508 hours, while that in December, 2008 and January, 2009, amounted to 27.0 percent of operation of 863 hours, among which 24.8 percent was due to the discharge in the RFQ. The long-term conditioning of the RFQ was necessary by shutting the gate valve between the RFQ and ion source. The conditioning was done with a short pulse and a high voltage, or sometimes the power was set at the level, where the multipactoring seemed to increase the vacuum pressure. The upgrade of the pumping speed is scheduled during this summer shut down by installing the cryopump and others. The back-up RFQ is also under design in parallel to be ordered soon.

CONCLUSION

The multi-purpose J-PARC accelerator is characterized by placing the 3-GeV RCS in between the 400-MeV injector linac and the 50-GeV MR. In order to realize the high beam power, many new technologies had to be developed. The developments were quite successful, resulting in the beam commissioning ahead or as scheduled. For this reason, not only the scientific and engineering outputs are foreseen, but also the technologies developed for the J-PARC accelerator will open up the new era for the field of the accelerator.

For example, in order to realize several MW pulsed spallation neutron source, the RCS scheme is promising since its beam current can be reduced by acceleration for the same beam power. The high-power RCS is also required by various future projects such as neutrino factories. Here, the higher field gradient acceleration is vital for these future projects.

The challenging development is still in progress as can be seen in this report. Bigger efforts are necessary for achieving the designed beam power reliably and stably.

REFERENCES

[1] KEK Report 99-4, JHF-99-3 and JAERI-Tech 99-056.
[2] Y. Yamazaki et al., PAC'99, THDL1 (1999).
[3] Y. Yamazaki et al., EPAC'00, THOAF201(2000).
[4] Y. Yamazaki et al., LINAC'00, TUD07 (2000).
[5] Y. Yamazaki, PAC'01, WOAA007 (2001).
[6] Y. Yamazaki, EPAC'02, TUZGB003, pp. 163 (2002).
[7] KEK Report 2002-13 and JAERI-Tech 2003-44.
[8] Y. Yamazaki, PAC'03, ROPA002 (2003).
[9] Y. Yamazaki, EPAC'04, TUPLT085 (2004).
[10] Y. Yamazaki, LINAC'04, TH101 (2004).
[11] K. Hasegawa, PAC'05, 220(2005).
[12] H. Kobayashi, EPAC'06, TUZAPA01 (2006).
[13] Y. Yamazaki, LINAC'06, MO1003 (2006).
[14] M. Kinsho, EPAC'08, THXG02 (2008).
[15] Y. Yamazaki, EPAC'08, THPP084(2008)..
[16] H. Kobayashi, PAC'09, WE1GR102(2009).
[17] H. Hotchi, PAC'09, TU6PFP090(2009).
[18] F. Tamura et al., PAC'09, TU6PEP068(2009).