

CHALLENGES AND SOLUTIONS FOR J-PARC COMMISSIONING AND EARLY OPERATION*

T. Koseki[#] and J-PARC accelerator group, J-PARC Center, KEK and JAEA, Tokai, Ibaraki, Japan

Abstract

Presented in this paper is an overview of commissioning status of the J-PARC accelerators. Recent progress of MR commissioning will be described in more detail. It focuses on the issues, challenges, solutions, and lessons learned during the commissioning and early operations of J-PARC.

INTRODUCTION

The J-PARC accelerator comprises an H⁻ linac, a Rapid-Cycling Synchrotron (RCS), a slow cycling Main Ring synchrotron (MR) and related experimental facilities. The RCS provides the 3-GeV proton beam to neutron and muon targets in the Materials and Life science experimental Facility (MLF) at a repetition rate of 25 Hz. A part of the beam extracted from the RCS (typically four pulses every ~3 sec) is injected into the MR, which accelerates the beam up to 50 GeV (30 GeV at the Phase 1 of the project) and delivers the beam to the hadron (HD) beam facility using a slow extraction (SX) system and to a neutrino (NU) beam line using a fast extraction (FX) system.



Figure 1: Bird's eye view of the J-PARC site.

Figure 1 shows a bird's eye view of the J-PARC site. The beam commissioning has begun at the upstream accelerators, while the construction of the downstream accelerators and experimental facilities is in progress. The line colours show the start year of beam commissioning in Japanese Fiscal Year (JFY). All the facilities started the beam commissioning on schedule. Beam commissioning of the linac and the RCS was started in November 2006 and October 2007, respectively. The MR and the MLF were started in May 2008. The HD facility and the NU beam line were started in Jan. 2009 and April 2009, respectively.

[#] tadashi.koseki@kek.jp

LINAC AND RCS

The linac consists of an H⁻ ion source, RFQ, DTL and separated-type DTL. The extraction beam energy is 181 MeV at present. Designed maximum peak current for the 181 MeV operation is 30 mA. Repetition is 25 Hz and pulse width is 0.5 msec in maximum. An energy upgrade project has been approved by the government already and the energy will be upgraded to 400 MeV by installing a new accelerating structure, Annular-Coupled Structure linac (ACS), in 2013.

The RCS has three-fold symmetry and a circumference of 348 m. Each super-period consists of two 3-DOFO arc modules and a 3-DOFO dispersion-free straight section. The arc module has a missing bend cell, which makes a high transition energy of 9 GeV, far beyond the extraction beam energy. The H⁻ beam from the linac is injected into the RCS by charge-exchange and painting injection.

Discharge Problem of RFQ

Since the autumn of 2008, the most urgent issue of the linac was discharge in the RFQ. The RCS beam power for the MLF users was limited at 20 kW due to the discharge in the RFQ. In order to solve the problem, we improved the vacuum system of the ion source and the RFQ sections in March 2009 and in 2009 summer shutdown period as shown in Fig. 2 [1]. The main subjects of the improvement are as follows;

- Pumping speeds were reinforced from 6000 to 9000 l/sec in the ion source section and from 3300 to 12500 l/sec in the RFQ section.
- Oil rotary pumps used for rough pumping were replaced with oil-free scroll pumps.
- A moisture filter was attached to hydrogen gas system in the ion source.
- A chamber of the Low Energy Beam Transport line (LEBT, a beam transport line between the ion source and the RFQ) was replaced with a new clean chamber having a divider plate with an orifice for differential pumping.
- A beam aperture at plasma electrode of the ion source was reduced from 9 mm to 8 mm to decrease the hydrogen gas flow from the ion source to the RFQ.

In addition, we performed in-situ baking of the RFQ section. As a result of the vacuum improvement, base pressure of the RFQ section was decrease to several $\times 10^{-7}$ Pa, a quarter of the pressure before the improvement. A long-term measurement of mass spectrum of the residual gases shows hydro-carbon components, which are thought to be coming from back streaming oil from the oil rotary

pumps, have been gradually decreasing during rf conditioning after the improvement.

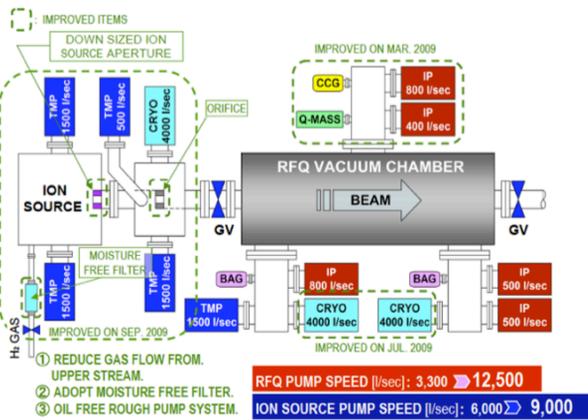


Figure 2: Vacuum system of the ion source and the RFQ sections.

The vacuum improvement recovered the performance of the RFQ. Figure 3 shows a history of beam delivery to the MLF. After the recovery of the RFQ, high power operation of the RCS became possible. The operation of 120 kW beam power has started in November 2009 for the MLF users.

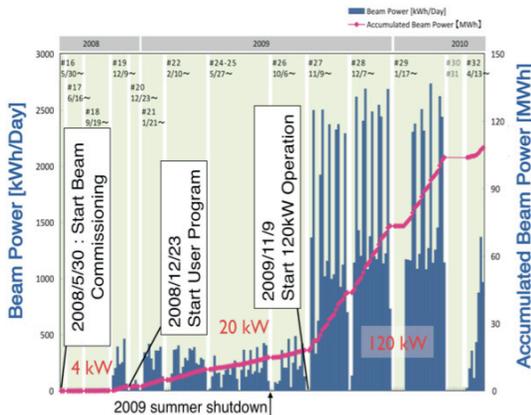


Figure 3: History of beam delivery to MLF (courtesy of M. Futakawa).

300 kW Operation

On December 2009, a high power operation of 300 kW was demonstrated in the RCS [2,3]. The 300-kW beam was successfully delivered to the MLF for one hour. The issue to be solved before starting the routine operation of 300 kW for the MLF users is beam loss. The beam loss for the 300 kW operation is 3~4 times larger than the loss for the 120 kW operation in the whole of the ring. Notable increases of the beam loss were observed at the downstream of the charge exchange foil and at the missing bend cells, which have the dispersion maximum.

The loss downstream of the foil comes from large-angle events of the foil scattering. It can be reduced by optimization of size and position of the foil [4,5]. We will

replace the current foil (foil size: 110 mm (H) × 40 mm (V)) with the smaller one (110 mm (H) × 15 mm (V)) in the 2010 summer shutdown.

The loss at the missing bend cells comes from the chromatic tune spread during acceleration. Sextupoles of the RCS are driven by DC power supplies, which are recycled ones from the 12-GeV Proton Synchrotron in KEK. The chromaticity is fully corrected only at the injection energy. AC power supplies are necessary to reduce the loss in the acceleration. We will install new AC power supplies for the sextupoles in the 2010 summer shutdown.

MR

The layout of the MR and the experimental facilities is shown in Fig. 4. The MR has three-fold symmetry and its circumference is 1567.5 m. An arc section consists of eight 3-FODO arc modules. Each of the arc modules has a missing bend cell. The MR is the first large proton accelerator that adopts the imaginary transition energy. It does not have the transition crossing between the injection and the extraction energies. The three dispersion-free 116-m long straight sections, each of which consists of 3-FODO cells and matching sections to the arcs at the both ends, are dedicated to “injection and beam collimators”, “slow extraction”, and “rf cavities and fast extraction”. The fast extraction system is bipolar, and it can extract the beam both inside (to the NU beam line) and outside (to abort beam line) the ring.

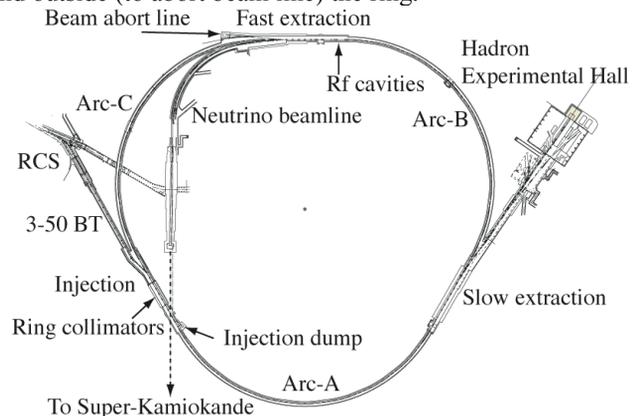


Figure 4: Layout of MR and experimental facilities.

Fast Extraction

The FX system delivers the beam to a graphite target of the T2K (Tokai-to-Kamioka) experiment via the NU beam line. The T2K experiment is long baseline neutrino oscillation experiment. The intense neutrino beam is sent to a large water Cherenkov detector, Super-Kamiokande (SK), which is located 300 km away from the J-PARC site.

The T2K experiment has started physics data taking in January 2010. So far, the maximum intensity of 70 kW has been delivered to the T2K experiment. The first neutrino event at the SK was observed on February 24, 2010.

Figure 5 shows the kinetic energy and circulating beam current measured by a DCCT in the FX operation. Two-bunch beam extracted from the RCS is injected into the MR in three times. The MR is operated with six bunches. The acceleration time is 1.9 sec and the cycle time of the FX operation is 3.52 sec. The extracted beam power is 65 kW in this figure. To reduce the space charge effect, both longitudinal painting and transverse painting are applied in the RCS [3]. The aperture of the MR collimator is set to be 54π mm-mrad for both horizontal and vertical directions to localize the beam loss on the collimator.

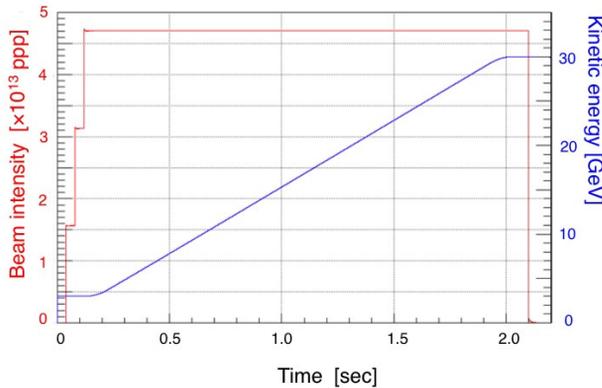


Figure 5: Intensity and kinetic energy of the FX operation.

Figure 6 shows a beam loss distribution measured by the beam loss monitors (BLM's) in the 65-kW operation. The horizontal axis is the address of the BLM's, which are distributed whole of the ring [6]. The vertical axis is loss count integrated for one shot. The beam loss is well localized on the ring collimator section. The most beam loss occurs in the injection timing and no beam loss is observed during the acceleration.

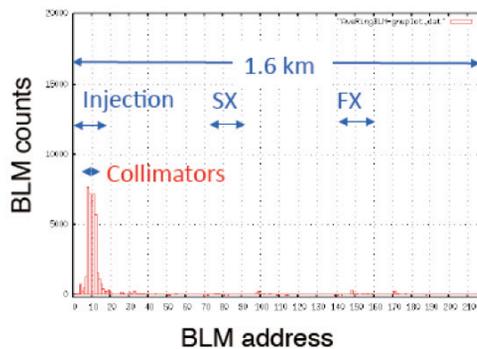


Figure 6: Beam loss distribution in the MR.

For higher beam intensity, resonance correction is essentially important to reduce the beam loss. Figure 7 shows a result of tune survey measured in the 3-GeV DC operation of the MR with low current beam of 4×10^{11} protons per pulse. Each symbol shows the beam survival ratio after 1.9 sec beam storage from the injection. The operating tunes for the FX (FX1~3) [7] and SX are shown in this figure. On the linear coupling resonance,

$\nu_x + \nu_y = 43$, large particle loss occurs. Correction of the linear coupling resonance is necessary for the high power operation on the tunes, FX2, FX3 and SX. We performed the resonance correction using vertical local bumps in two sextupoles, SDA019 and SDB028. A pair of bump heights of +4mm in SDA018 and -5 mm in SDB028 is effective for reducing the beam loss [8]. Figure 8 shows the beam intensities measured by the DCCT for the operation on (22.2, 20.8) with and without the resonance correction.

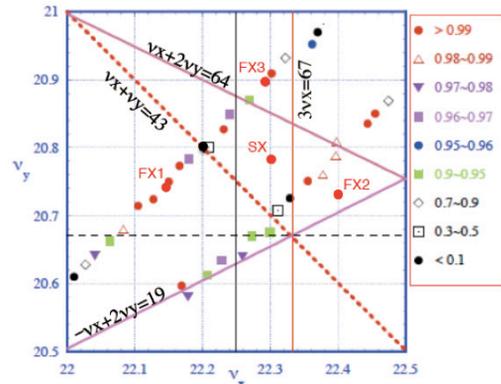


Figure 7: Results of tune survey with low current beam.

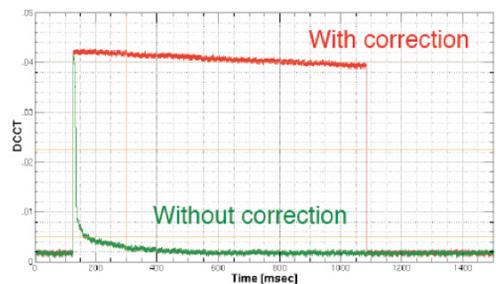


Figure 8: Beam intensities for 3-GeV DC operation on (22.2, 20.8) with and without the linear coupling resonance correction.

We have performed a demonstration of 100 kW equivalent beam operation of the MR with single shot mode. The extracted particles to abort beam dump is 7.2×10^{13} protons per pulse with the six-bunch operation. Beam loss is almost localized on the collimator section in the injection timing. The loss is about 7.7×10^{11} , which is corresponding to ~ 100 W, while the design capability of the collimator is 450 W at the present. We will soon start the continuous 100-kW operation for the T2K experiments.

Slow Extraction

The SX system delivers the beam to the HD experimental facility. At present, three beam lines, KL, K1.8, K1.8BR are open for users of particle and nuclear physics experiments in the HD facility. So far, the maximum beam power of 2.8 kW has been delivered to HD facility. We have successfully observed charged and neutral kaons in all of the three secondary beam lines.

For the SX [9], we have four bump magnets, two electrostatic septa, ten magnetic septa in the straight section, which is connected to the HD beam line (a beam transfer line between the MR and the HD facility). Eight sextupoles to excite third integer resonance, $3\nu_x=67$, are located in the arc sections. For the SX, the horizontal tune is gradually ramped up to the resonance line by changing one of the quadrupole families, QFN, which has 48 magnets and located in the arc sections.

Figure 9 shows beam spill measured by a photomultiplier with a plastic scintillator in the HD beam line. The extracted beam spill has many sharp peaks, which come from fluctuation of tune. Tune is fluctuating about ± 0.003 during the extraction. The cause of the fluctuation is current ripple of the main magnet power supplies.

We define the duty factor of the spill as

$$Duty = \left(\int_{T1}^{T2} I(t) dt \right)^2 / \int_{T1}^{T2} dt \int_{T1}^{T2} I(t)^2 dt, \quad (1)$$

where $I(t)$ is the beam spill intensity, $T1$ and $T2$ define the time gate width. For the spill signal shown in Fig. 11, the duty factor is calculated to be $\sim 1\%$.

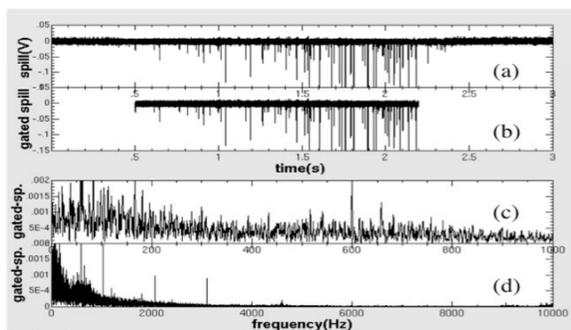


Figure 9: Beam spill measured by a photomultiplier with a plastic scintillator in the HD beam line: (a) beam spill, (b) beam spill with time gate between 0.5 and 2.2 sec, (c) FFT of the gated spill with 1 kHz span, (d) FFT of the gated spill with 10 kHz span.

In the 2009 summer shutdown, we installed a spill feedback system, which consists of two types of quadrupoles and a DSP system [10]. The beam spill signal is fed into the DSP system and current patterns of the correction are sent to power supplies of the feedback quadrupoles. The quadrupoles, named Extraction Q (EQ) and Ripple Q (RQ) are adopted to make a constant spill shape in the overall time of the extraction and to compensate the fine ripple structures, respectively.

The other approach to improve the spill structure is “trim coil short” method [11]. In the MR, all the quadrupoles have 24 turns main coil and 11 turns trim coil on each pole. We set a MONFET relay to the trim coil circuit. When the trim coil is shorted by the relay, the ripple components of the main coil current is bypassed to the trim coil and the magnetic field ripple is reduced.

A result of field measurement shows the field ripple on the flat top is reduced by 1/6 by the trim coil short [11].

Figure 10 shows a typical beam intensity of the SX operation for the HD facility users. After the acceleration, beam is extracted for 2 sec. The cycle time for the slow extraction operation is 6 sec. The extracted beam power is 1.9 kW in this figure. The spill feedback is switched on and the trim coils are shorted in 133 quadrupoles out of total 216 quadrupoles. Beam spill signal of the same shot is shown in Fig. 11. The spill structure is improved and the calculated duty factor is 11%.

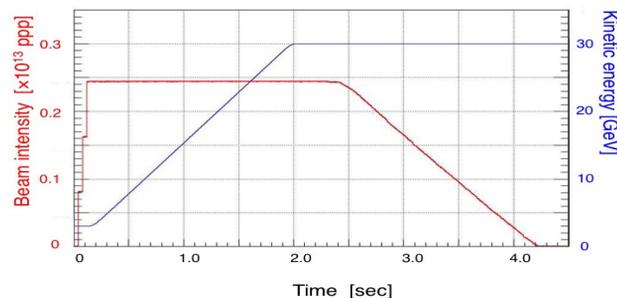


Figure 10: Intensity and kinetic energy of the SX operation for the HD facility users with spill feedback and trim coil short.

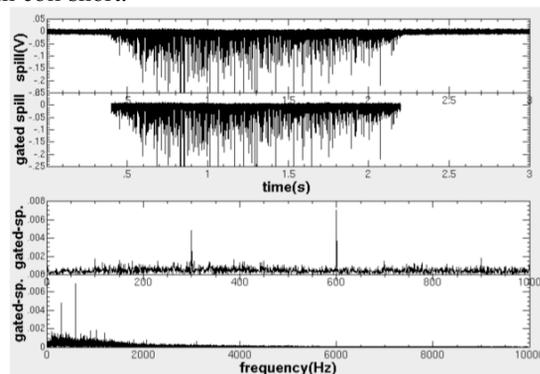


Figure 11: Beam spill with the “spill feedback ON” and “trim coil short”.

For the SX, one of the most critical issue is radio-activation of the components. A high extraction efficiency is required to avoid being exposed to radiation in hands on maintenance. At present, the extraction efficiency is estimated using the DCCT and BLM signals to be 98.5 %.

The residual activation in the SX section in one week after the five days operation with beam power 1~1.5 kW was less than 100 μ Sv/h on contact measurement. The guideline of residual-activation maximum for the SX section is less than ~ 1 mSv/h on one foot distance. We will increase the beam intensity monitoring the residual activation level carefully.

MR Plan for JFY2010

After run in June 2010, we have three-month shutdown. For the MR, the following improvements in the shutdown are planned.

- Installation of additional iron shields in the collimator section of 3-50 BT (a beam transport line between the RCS and MR): Loss capacity will be increase from 0.45 kW to 2 kW.

- Replacement of the FX kicker system: The present kicker system has a rise time of 1.6 μ sec. It is larger than a required rise time for the originally designed eight-bunch operation. In addition, the heating problem in the ferrite cores occurs in the recent high-power operation. New kicker system has faster rise time less than 1 μ sec. The eight-bunch operation will be available from the October run. Now we are carefully investigating the beam coupling impedance of the new kicker system.

- Installation of 2nd harmonic cavity: The cavity can be used also as a fundamental cavity to increase accelerating voltage.

For the SX, the following studies are now in progress for more improvement of spill time structure:

- Tuning main power supplies to reduce 600 Hz ripple.
- Ripple reduction using RF noise [12].
- A feed forward system to cancel the 50 -100 Hz field ripple using the trim coils.

For higher extraction efficiency, dynamic bump scheme will be adopted from the 2010 autumn run.

RF CORES OF SYNCHROTRONS

Both the RCS and the MR use MA (Magnetic Alloy) loaded rf cavity [13]. The rf system has following features; high field gradient larger than 20 kV/m, no tuning loop because of the broadband rf characteristics, and a high reproducibility by precise control system using full digital LLRF. The RCS and the MR have eleven and five rf cavities, respectively. One cavity consists of six tanks and three accelerating gaps. Three cores are installed in each tank, which is filled with cooling water. While a core type of the RCS is "uncut core", the MR is "cut core" to obtain a larger Q-value of ~26.

In the early operation years, we have met impedance reduction for both the RCS and MR cavities [14]. For the RCS cavities, the impedance reduction due to core buckling and crack has been observed three times. They are caused by deformation due to thermal stress. To decrease the stress, we improved the manufacturing process of cores. In the new process, the cores are manufactured without impregnation of epoxy resin. The new cores have been installed in one of the RCS cavities in March 2010. We are observing their impedance carefully in the RCS operation.

For the MR cavities, the first impedance reduction was observed in autumn of 2009. Although the cause is now under investigation, it is supposed to be relating with corrosion of cutting surface of the cut cores. Draining the cooling water and exposure the cores to the air recover the impedance. Re-polishing the cutting surface is also effective to recover the impedance. As more effective solution, a SiO₂ coating on the cutting surface is now under development to prevent the corrosion. Test cores treated with the SiO₂ coating was manufactured and

installed in a cavity on a test bench. Continuous high power test of them is now in progress.

SUMMARY

The J-PARC accelerator commissioning and early operation for users are in progress. Performance of RFQ was recovered by the improvement of vacuum system. For the MLF users, 120-kW routine operation is continued and 300-kW operation for 1 hour was successfully demonstrated. The MR delivers the beams of 70 kW maximum by the FX and 2.6 kW maximum by the SX to the T2K experiment and the HD beam facility, respectively. Though we still have issues to be solved, we continue the challenge to higher power and more stable operation finding solutions and acquiring operation experiences.

REFERENCES

- [1] K. Hasegawa *et al.*, "Status of the J-PARC RFQ", in these proceedings.
- [2] M. Kinsho *et al.*, "Status and progress of the J-PARC 3 GeV RCS", in these proceedings.
- [3] H. Hotchi *et al.*, "High Intensity Beam Operations in the J-PARC 3- GeV RCS", in these proceedings.
- [4] H. Harada *et al.*, "Study of Uncontrolled Beam Loss Due to the Foil Scattering at the 3-GeV RCS of J-PARC", in these proceedings.
- [5] P. K. Saha *et al.*, "Systematic Beam Loss Study Due to the Foil Scattering at the RCS of J-PARC", in these proceedings.
- [6] T. Toyama *et al.*, "Beam Loss Monitoring using Proportional Counters at J-PARC", HB2008, WGF03.
- [7] A. Molodozhentsev *et al.*, "Study of the Beam Dynamics for the Fast Extraction Operation Scenario of the J-PARC Main Ring", in these proceedings.
- [8] J. Takano *et al.*, "Magnetic Pattern Control System of the J-PARC Main Ring", in these proceedings.
- [9] M. Tomizawa *et al.*, "Status and Upgrade Plan of Slow Extraction from the J-PARC MR", in these proceedings.
- [10] A. Kiyomichi *et al.*, "Beam Spill Control for the J-PARC Slow Extraction", in these proceedings.
- [11] S. Igarashi *et al.*, "Magnetic Field Ripple Reduction of Main Magnets of the J-PARC Main Ring using Trim Coils", in these proceedings.
- [12] A. Schnase *et al.*, "Application of Digital Narrow Band Noise to J-PARC Main Ring", in these proceedings.
- [13] M. Yoshii *et al.*, "Recent Status and Future Plan of J-PARC MA Loaded RF Systems", in these proceedings.
- [14] M. Nomura *et al.*, "Condition of MA Cores in the RF Cavities in J-PARC Synchrotrons after Several Years of Operation", in these proceedings.