OPERATIONAL EXPERIENCE WITH J-PARC INJECTION AND EXTRACTION SYSTEMS

P.K. Saha*[1)] for the J-PARC team[1),2)],
[1)] Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan,
[2)] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

Abstract

The Japan Proton Accelerator Research Complex (J-PARC) is now in a full operational stage and delivering relatively high power beam to all experimental facilities. There are two stages of injection and extraction schemes in the entire facility and each has very unique as well as common issues in terms of the design criteria in order to obtain a desire beam power in each stage and finally to ensure a stable and fair operation keeping the beam loss to an acceptable limit. There has been a lot of understandings and achievements so far through systematic beam studies and thus continuing the user operations with relatively a high power beam to all experimental facilities. However, for further higher and long term operation, there remains few issues as well as challenges to discuss. Uncontrolled beam loss due to the foil scattering at the RCS injection area, slow rise time and heating problem with the fast extraction kicker system as well as improvement of duty factor for the slow extraction operation in the MR can be mentioned.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high intensity accelerator project consists of a 400 MeV linac (181 MeV at present), a 3 GeV rapid cycling synchrotron (RCS), a 50 GeV (30 GeV at present) main ring (MR) and several experimental facilities [1]. The experimental facilities include a Material and Life Science Experimental Facility (MLF), which utilizes a 3 GeV fast extracted beam from the RCS, while the neutrino (NU) and the hadron (HD) experimental facilities use 30 GeV fast and slow extracted beam, respectively, from the MR. The entire accelerator facility already entered into an operational mode ending with its overall initial beam commissioning aspects. The RCS is now operating with a beam power of 120 kW for the MLF and more than 200 kW equivalent beam power for the MR injection. The MR already achieved a maximum possible of 6 bunches injection and continuing NU operation with a beam power of more than 50 kW through Fast Extraction (FX) at 30 GeV. The Slow Extraction (SX) operation there also for the HD experimental facility with gradually improving the duty factor is in a good progress. On the other hand, a maximum beam power of 300 kW already been demonstrated in the RCS, while the MR also demonstrated a 100 kW operation for the neutrino experiment [2, 3].

There are two stages of injection and extraction in the entire system. An H^- beam with a kinetic energy of 181 MeV from the linac is injected into the RCS. RCS has a charge-exchange H^- painting injection scheme in the injection period of 500 μs. Accelerated is done up to a beam energy of 3 GeV and the beam is then simultaneously extracted for the MLF and MR injection by using a pulsed bending magnet placed in the extraction beam transport line. The MR has a multi-bunch injection scheme and starting with a 3 GeV injection, the beam is accelerated up to a maximum of 30 GeV at present. The beam is then delivered either to the neutrino experiment through FX mode or to the hadron experimental facility through SX mode.

In order to obtain a high power and high quality beam and eventually for a fair and stable operation, there are many issues and challenges in each accelerator especially, with the injection and extraction systems of both RCS and MR. Some of the issues are common but most of the issues are quite different in many aspects. Because of a charge-exchange scheme, the RCS injection system involves many more issues and thus needed to adopt a complicated and a sophisticated system as compared to the MR injection. The charge-exchange foil including the foil system itself is one of the most complicated issue in the RCS injection. On the other hand, the SX scheme of MR is quite different than the ordinary RCS extraction, where a high duty and a low loss operation are always big issues. The overall initial operational experiences with both injection and the extraction systems are satisfactory and there also has a lot of understandings through systematic beam studies and simulations especially, with a high power beam. However, there remains few urgent issues for further higher power and stable operation in the near future. The uncontrolled beam loss due to the foil scattering at the injection area during multi-turn injection period is one of main issue in RCS for high power operation. The leakage field from the extraction and injection magnets in RCS and MR, respectively, are two big issues. Furthermore, slow rise time of the FX kicker system, hitting problem in the kicker ferrite core are two recent issues and appear as direct limitations for high power SX operation to the NU experiment, where a high duty regardless of high power for the HD experimental facility is one of the key issue with SX operation in the MR.

RCS INJECTION AND EXTRACTION SYSTEMS

One key issue with the RCS injection is to keep the uncontrolled beam loss especially, from the foil scattering as low as possible. Based on detail study on the transverse

* E-mail address: saha.pranab@j-parc.jp

painting injection [4], an optimized painting injection area is set for the user operation in order to reduce the circulating beam hitting time on foil and eventually to minimize the foil scattering loss. The extraction system is performing well and there is no significant issue at least with the present operation. As a result, MLF user operation with a beam power of 120 kW and nearly with 200 kW equivalent operation or more for the MR injection are continuing without any serious issue. However, for further higher power and a long term operation in the near future keeping the beam loss within acceptable limit as well as operation with very low downtime of the accelerator, there are some issues to discuss.

Issue on Foil Life Time

For the charge-exchange injection in RCS, a HBC (Hybrid type Boron-mixed Carbon) foil is used [5]. Although RCS is operating with much lower beam power than its design beam power of 1 MW, the life time of the foil not yet appears as a real issue. A single foil is in use for a year with a beam power of almost 120 kW to the MLF user in each run and similar or higher power equivalent beam for the MR injection. The transmission efficiency with the same operational condition of RCS remains unchanged and so far no noticeable deterioration of the foil could be seen [6].

On the other hand, waste beam at the H0 dump line is monitoring online through a special technique as there is only about a 0.4% of the unstripped beam are suppose to remain by using the present thickness of the stripping foil. The raw signal taken by a Current Transformer(CT) named as H0CT placed at the entrance of the dump contains a large noise from the nearby bump magnets as well as main magnets and thus hard to pick up the beam signal. However, a FFT (Fast Fourier Transform) analysis of the raw spectrum and picking up the signal that corresponds to the ring RF frequency (fundamental) at the bottom energy makes it possible to identify the beam signal well separated from the noise signal, in other words with a good S/N ratio. Figure 1 shows a trend of the H0CT although just for 10 days taken during a recent MLF user operation. The trend of the linac beam peak current at the upstream part is also shown together for comparison, where the H0CT trend is found to be well reflected the peak current of the linac beam. In addition, an off-line analysis is also carried out at each run and that shows the waste beam there at the H0 dump is $(0.38\pm0.05)\%$ and is thus consistent with expectation. This study is in other words a very direct way of monitoring the foil life time and becomes important for the high power operation.

Foil Scattering Issue

The uncontrolled beam loss caused by the nuclear scattering especially, by the large angle multiple Coulomb scattering is the most considerable issue in the RCS injection. Figure 2 shows a close view downstream of the RCS injection area. Two hot points represented by "(1)" and "(2)" are

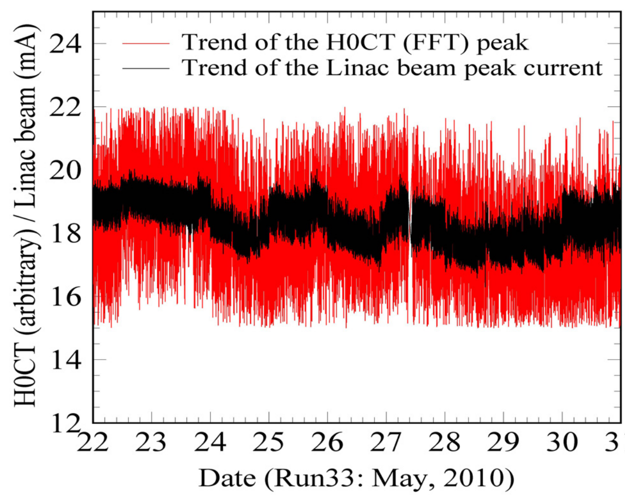

Figure 1: Partial trend of the H0 dump CT taken during run 33 representing the waste beam at the dump. Life time of the stripping foil can be monitor through such a technique. See text for detail.

located at the ring inner side and peaking only in the horizontal direction as shown by two arrows. The 1st point is at the H0 dump branch, while the 2nd point is at a little upstream of the ring QFM (BPM2-1). Typically, there exist a residual radiation of 1$\sim$2 mSv/h (on contact) after each run with a beam power of 120 kW operation (0.1$\sim$0.2 mSv/h at 30 cm apart). In order to identify the loss sources, a detail experimental study as well as simulation were carried out, where the real experimental condition, a comparatively large number of macro particle as well as a very realistic and precise machine aperture were taken into account. As a result, a very realistic distribution of the beam loss peaking exactly at (1) and (2) and consistent with the beam loss monitor signal were obtained. The study were extended for RCS different operation mode so-called "one third (1/3) mode" and "DC circulating mode" [8] and also with different painting area in the transverse direction. In the former mode, the beam passes through the foil only once and thus the average foil hit is just 1, while in the later mode it is practically much higher and depends on the painting area. For the present 120 kW operation with a painting area of 150 π mm mrad, the average foil hit is calculated to be about 9. Figure 3 shows a comparison of the measured beam loss rate to that with the simulation. The beam loss monitor gain for each mode was adjusted and was different in order to measure even a lower beam loss for the former mode or the signal not to saturate in case of much higher beam loss for the later mode. The experiment was done for three different painting areas of 100, 150 and 200 π mm mrad in the horizontal direction. The loss particles found in the simulation and integrated beam loss monitor signal for each case were normalized by the data with a painting area of 150 π mm mrad. The trend of the beam loss rates were found to be consistent each other and were very proportional to the foil hitting rate. It is important to mention here that, the bigger the horizontal painting area the larger the aperture at the ring inner side of 1st loss point (1) and thus beam loss at that point reduces with larger painting area [7]. On the other hand, there are no noticeable loss as well as residual activation in the vertical direction because of the vertically focusing quadrupole QDL as confirmed in the simulation too.

In order to reduce such a uncontrolled beam losses, two actions are in consideration. The first one is to use a smaller size foil and is very simple to adopt. It will directly reduce such a beam loss as the foil hitting particles will be reduced. The present foil size especially in the vertical direction is quite big (40 mm) and already replaced with a size of 15 mm as shown in Fig. 4. However, there is no change in the horizontal direction as foil position is adjustable very precisely and also circulating beam orbit goes away from the foil with decay patterns of the horizontal painting bump magnets. The foil hitting rate are expected to reduced about a half and thus the corresponding beam losses as well. However, for further high power and long term operation, radiation level at those areas might cross the acceptable limit and thus the 2nd action is to place a new collimator system at the H0 branch location (1st loss point) in order to localize those uncontrolled beam losses and will be installed in the 2011 maintenance period.

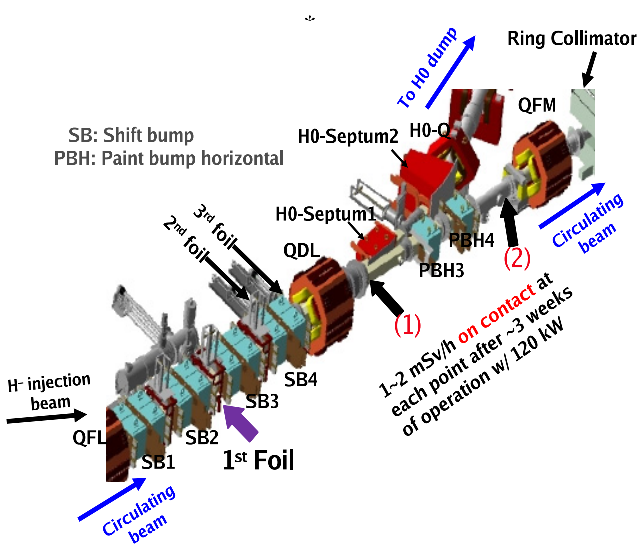

Figure 2: Close view around the RCS injection area. Two hot beam loss points in the ring inner side caused by the foil scattering are shown by arrows in "(1)" and "(2)". A smaller size foil by which a half of the beam loss can be reduced has already been installed and for further measures putting a local collimator system at "(1)" in order to localize beam loss is also in consideration.

Leakage Field from the Extraction DC Magnets

The effect of the leakage field from the extraction DC septum magnets and one bending magnet in the 3NBT line is one big issue with RCS [8]. Even with extra shielding, the integrated leakage field was suppressed only less

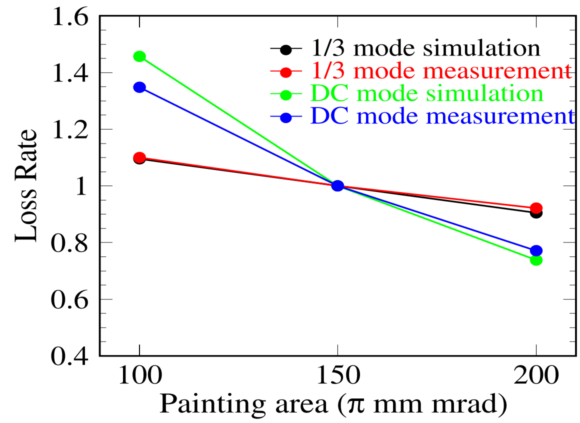

Figure 3: Beam loss rate with different foil hitting rate at the loss point "(1)". Comparison of the loss monitor data and the simulated results for each mode and setting are found to be consistent with each other. A similar consistency is also found for the same comparison of the beam loss at "(2)".

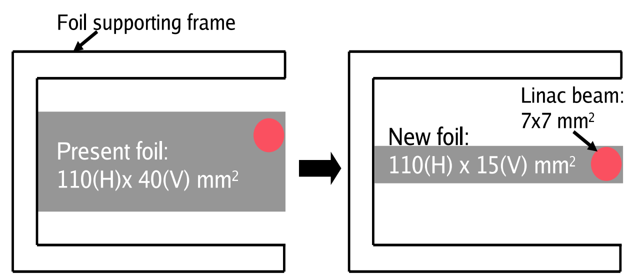

Figure 4: A new foil size with almost the same size of the linac beam in the vertical direction is already installed. The foil hitting rate and thus the corresponding beam losses will be reduced nearly half as compared to that with the present foil used even with a vertical offset position.

than a half and that still cause the COD (Closed Orbit Distortion) as high as $\pm 8mm$ in the horizontal direction and about $\pm 2mm$ in the vertical direction. Although the COD caused by such a leakage field can be well corrected by using steering magnets but as it includes higher order field components such as quadrupole component, causing a distortion of the superperiodicity and additionally exciting several nonstructure betatron resonances [8]. There are almost no space available for further shielding and thus by introducing 2$\sim$3 small quadrupole magnets in the extraction straight section of the RCS ring so as to use as local correctors are in consideration.

Issue with RCS Extraction Kicker System

The life time of the thyratrons and a stable operation of the kicker system may be also two considerable issues with the RCS extraction. There are 8 kickers and power supply of each kickers has two thyratrons. Recent studies revealed that a proper conditioning and ranging methods and then a proper setting of the rise time increased thyratrons life time significantly as compared to a very poor life time in the early operations believe to used without such detail measures [9]. In addition to the life time, accelerator downtime related to kicker failures and thyratron exchange becomes almost negligible in the recent operation. In addition, there has been introduced a online feedback program in order to control time delay of the thyratron output current, in other words drift of the kicker. The online program corrects the thyraton time delay automatically and thus there is no need to set a higher reservoir voltage for any thyratron as was done before to minimize the drift. This is also proved to be one good reason of almost no kicker failure during user operation after introducing the feedback program.

We have also performed extraction with 7 kickers in stead of 8 kickers in the usual design. The purpose of the study was mainly to established a backup scenario to continue user operation in case of any problem with any kicker. It could be even applied during a thyratron exchange, which takes several hours and thus beam delivery can be continued with 7 kickers. The scheme includes a horizontal local bump orbit of about 10 mm produced by the closed orbit correction steering magnets at the kicker region and the rest are just fine adjustment with extraction DC septum magnets in order to obtain the original extraction orbit. The study was done with a beam power of maximum 120 kW at the RCS extraction and there was no unexpected loss observed for any combination with 7 kickers operation.

MR INJECTION AND EXTRACTION SYSTEMS

The 50 GeV (30 GeV at present) performs multi bunch proton beam injection from the 3 GeV RCS and has two different extraction schemes [1]. The 30 GeV beam is delivered either to the neutrino experiment through Fast Extraction (FX) channel or to the hadron experimental facility through Slow Extraction (SX) channel. Figure 5 shows a demonstration of the MR operation cycle. An increase of the beam intensity due to the multi bunch injection is represented by the “MR Beam”, while the magnet pattern is shown by the red line. In the fast extraction, the beam is immediately extracted at the top energy of 30 GeV, while in the slow extraction, beam is slowly extracted by exciting 3rd order resonance with sextupole magnets and ramping the horizontal betatron tune during the extraction period of 2 s. So far in the operation, the MR cycle is fixed to be 3.52 s and 6s, for FX and SX operation, respectively, while the acceleration as well as injection time are same for the both operation.

There has been a lot of progresses in the beam commissioning of MR and thus comparatively high power operation for the neutrino experiment as well as gradually stable operation for hadron experimental facility has already been started [2, 10]. Neutrino user operation has already been started few months ago and at present continuing with a beam power of about 50 kW. Demonstration for a further higher power operation with 100 kW beam was also succeeded recently but unfortunately, due to the heating problem in the ferrite core of the FX kicker magnets such a operation could not started yet. Except that issue, the beam in the injection and extraction was in control and well localized in the ring collimator section [10]. As for the SX operation, a maximum beam power of 2.6 kW has been delivered to the HD experimental facility with an extraction efficiency better than 98% but relatively with a low duty factor of around 11%. The strategy with SX operation is to increase the beam power gradually and in addition the HD facility is now at the commissioning stage and there has limitation on the HD beam dump capacity too.

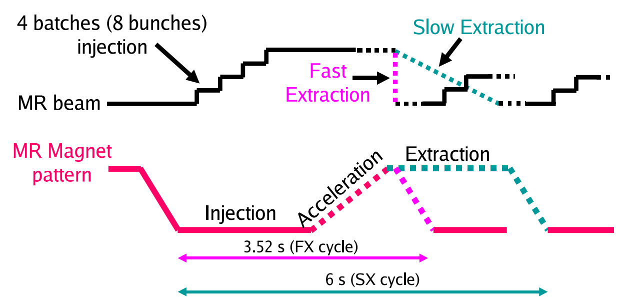

Figure 5: Operation cycle of the MR.

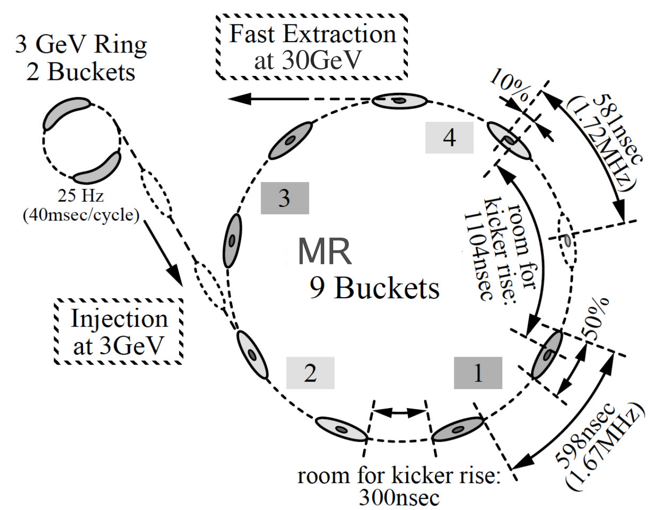

Figure 6: Bunch configuration in the main ring.

Like RCS, there has also several key issues with MR injection and extraction systems especially, with high power operation. The leakage field from the injection Eddy current septum can be mentioned. However, additional shielding has already been put in this summer maintenance period hoping to reduce the leakage field down to 10%.

Issues with FX Kicker System

There are two issues with the present FX kicker system of the MR and both of which related to high power operation. One is the slow rise and the other one is the heating problem in the ferrite cores as mentioned above. Figure 6 shows the bunch configuration in the MR [1]. For a full 8 bunches operation, rise time of the FX kicker system is needed to faster than $\sim 1.1\mu$ s. The rise time of the present system is as slow as 1.6μs and thus 8 bunches operation is not possible in principle. On the other hand, there occurred a heating problem in the ferrite core of the kicker magnets in the recent high power operation larger than 60 kW, which eventually results a drift the beam orbit and goes beyond the criteria of $\pm$1mm at the NU experimental target. The high power operation with larger than 60 kW beam could not thus continued for a long term. In fact, the present kicker system was not made to perform a design operation with 750 kW but did not expect to show such a effect with a beam power of 100 kW. In order to solve these two issues, the present kicker magnets together with the system has already been replaced recently. A careful investigation of the coupling impedance has also been done. The design 8 bunches operation is thus possible and the new FX kicker system is believe to have no any problem even for an operation with a design beam power of 750 kW.

Slow Extraction Issue

One of the main parameter in SX operation is the so-called spill duty factor, which is a function of the beam spill flatness. The beam spill is a time structure of the slow extraction and is required to be as flat as possible in order to prevent pileup events in particle detectors or data acquisition system for the physics experiments.

The spill duty factor is defined as

$$Duty\,Factor = \frac{\left[\int_0^T I(t)dt\right]^2}{\int_0^T dt \cdot \int_0^T I^2(t)dt}, \qquad (1)$$

where, $I(t)$ is the spill intensity and T is the time duration of the slow extraction. In order to make a flat beam spill structure from the original Gaussian like beam spill intensity, a spill feedback system has already been successfully installed and tested. A duty factor of about 2$\sim$3$\%$ without using the feeback system was drastically improved to about 11$\sim$12$\%$ by introducing the feebback system [11, 2]. Unfortunately, due to large ripple in the power supply of the main magnets, the spill structure could not be made further flat and eventually there had big intensity fluctuation of the beam spill. However, there are several studies are in progress such as ripple reduction through tunning of the main power supply, introducing a transverse RF noise [12] as well as a new algorithm for the spill feedback system and will be tested in the next beam study time.

SUMMARY

The overall experience so far with the J-PARC injection and extraction systems is satisfactory. The entire complex is in the operational stage relatively with a high power beam for all experimental facilities. There are several issues especially, for further higher beam power and long term operation and most of which are fairly understood and thus many measures have already been taken in this summer maintenance period. A smaller size foil is installed in order to reduced uncontrolled foil scattering beam loss at the RCS injection and also a local collimator system will be installed at the H0 branch to localize all uncontrolled beam losses at that region. The FX kicker system in the MR has already been replaced with a new one with a rise time faster than $1\mu s$. The 8 bunches operation is now possible and also hope no further issue even for an operation with a design power of 750 kW. There are also several measures and will be implemented soon in order to improve the duty factor for the SX operation. It is thus hope that there would be no practical limitations from any of the injection and extraction scheme for continuing a stable and high power user operation in the J-PARC.

REFERENCES

[1] “Accelerator Technical Design Report for High Intensity Proton Accelerator Facility Project”, JAERI Technical Report, 2003-044.

[2] T. Koseki, “Challenges and Solutions for J-PARC Commissioning and Early Operation”, IPAC10, Kyoto, Japan, 2010, TUYRA02, pp. 1304-1308.

[3] H. Hotchi et. al., “High Intensity Beam Operations in the J-PARC 3-GeV RCS”, IPAC10, Kyoto, Japan, 2010, MOPEC068, pp. 624-626.

[4] P.K. Saha et. al., Phys. Rev. ST Accel. Beams 12, 040403 (2009).

[5] I. Sugai et. al., Nucl. Inst. and Meth. A 613 (2010) 457-461.

[6] M. Yoshimoto et al., “Beam Study Results with HBC Stripping Foils at the 3-GeV RCS in J-PARC”, IPAC10, Kyoto, Japan, THPEB020, pp. 3927-3929.

[7] K. Yamamoto, “Beam Loss and Residual Dose at 100kW User Operation in the J-PARC Accelerator”, HB2010, Morschach, Switzerland, 2010, TUO2C06.

[8] H. Hotchi et. al., Phys. Rev. ST Accel. Beams 12, 040402 (2009).

[9] M. Watanabe et al., “Operation of Kicker System using Thyratron of the 3 GeV Rapid Cycling Synchrotron of J-PARC”, IPAC10, Kyoto, Japan, 2010, WEPD086, pp. 3296-3298.

[10] T. Koseki, “High Intensity Aspects of the J-PARC Facility”. HB2010, Morschach, Switzerland, 2010, MOIB02.

[11] A. Kiyomichi et al., “Beam Spill Control for the J-PARC Slow Extraction”, IPAC10, Kyoto, Japan, 2010, THPEB022, pp. 3933-3935.

[12] A. Schnase et al., “Application of Digital Narrow Band Noise to J-PARC Main Ring”, IPA10, Kyoto, Japan, 2010, TUPEA051, pp. 1446-1448.