

RECENT COMMISSIONING OF HIGH-INTENSITY PROTON BEAMS IN J-PARC MAIN RING*

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Abstract

J-PARC main ring (MR) provides high power proton beams of 200 kW to the neutrino experiment. Beam losses were well managed within capacity of collimation system. Since this beam power was achieved by shortening the repetition rate, the following tunings were applied in order to reduce the beam losses, such as improvement of tune flatness, chromaticity correction, upgrades of injection kickers, dynamic bunch-by-bunch feedback to suppress transverse oscillation, beam loading compensation using feedforward technique, and balancing the collimators of MR and the injection beam transport line. Especially, the dynamic bunch-by-bunch feedback was effective to reduce the beam losses to one-tenth during injection and beginning of acceleration. Moreover, with the beam loading compensation, impedance seen by the beam was significantly reduced, longitudinal oscillations were damped, and the beam power was increased over 5% without increasing the beam losses. Monitors were upgraded to find time structure and location of the beam losses, even in first several turns after each injection. In this presentation these commissioning procedures and beam dynamics simulations are shown, and our upgrade plan is discussed.

OVERVIEW

The Japan Proton Accelerator Research Complex (JPARC) consists of a series of three proton accelerators, a H⁻ linac, a 3 GeV Rapid-Cycling Synchrotron (RCS) and a Main Ring synchrotron (MR), and three experimental facilities [1]. Typically more than 93% of the 3 GeV protons from RCS are directed to muon and neutron production targets in the Materials and Life Science Experimental Facility (MLF). The rest protons are transported into MR through a beam transport (3-50BT) and accelerated to 30 GeV, and extracted with the fast extraction method (FX) or the slow extraction method (SX). The protons into the SX line are guided to the hadron experimental facilities, and the protons into the FX line are delivered to the neutrino target for the Tokai to Kamioka Japan (T2K) experiment. A different operational period is set for each extraction method. In the high power operation of MR in FX mode, 145 kW proton beams had been delivered to the neutrino target by March 2011, before the Tohoku earthquake, and 200 kW

by June 2012. The repetition time had been shortened from 3.2 s to 2.56 s. The beam power was increased with controlling the beam losses to be localized at the MR collimator area and the averaged lost power under 450 W, the collimator capacity till this summer. In the next section, the tunings to reduce the beam losses, the monitoring properties during the tunings, and our near upgrade plan are discussed.

HIGH-INTENSITY OPERATION

MR high-intensity operation in the FX mode restarted on December 24th, 2011 after the 9-month-shutdown from March 11th, 2011. User operation for the T2K experiment restarted on March 5th, 2012, and continued till June 9th, 2012. Figure 1 shows the history of the MR power, and Figure 2 shows the total beam losses during the period. The achieved beam power to the neutrino target was 190 kW in May, 2012, and 200 kW in June, 2012, the latter of which signified $1.08E14$ protons per pulse (ppp) in 2.56 s cycle. The beam losses were measured with DC current transformer (DCCT). In Fig. 2, the red line is the loss power based on 1 ms averaged DCCT signal, and the green line based on 10 μ s DCCT signal. Except for machine study periods, the total beam losses during the user operation were successfully controlled below the collimator capacity, which was 450 W. It will be 2 kW in this fall. The delivered protons on the neutrino target were $\sim 3E20$ POT (protons on target) from January, 2010, the beginning of the T2K user operation, to June 9th, 2012. The T2K experiment observed 11 candidate events, where a muon neutrino appeared to be transformed into an electron neutrino. The transformation from muon neutrino to electron neutrino occurs with 99.92% probability (3.2 sigma) [2].

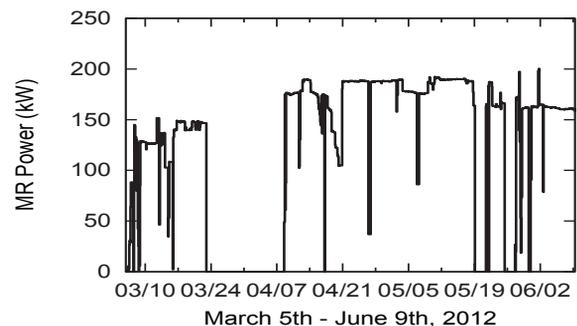


Figure 1: MR beam power in the FX mode from March 5th to June 9th 2012. 190 kW in mid-May, 200 kW in June.

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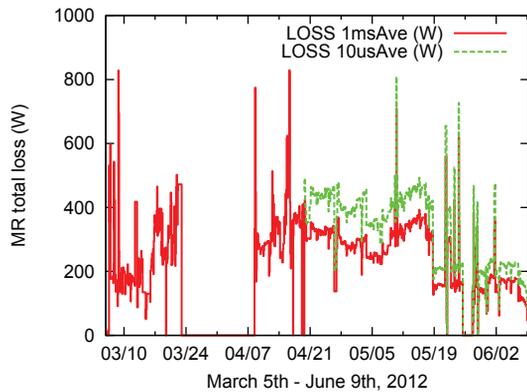


Figure 2: MR total beam loss in the FX mode from March 5th to June 9th 2012. Collimator capacity was 450 W.

Improvements during the Shutdown in 2011 and the Corresponding Beam Commissioning

In the beam commissioning from December 2011 to March 2012, the beam power was increased gradually in order to discharge the absorbed gas in the vacuum chamber. Tunings were performed, corresponding to several of the MR improvements achieved during the 9-month-shutdown last year, which concerned beam properties:

- Re-alignment of main magnets [3]. Beam tunings: Beta functions, dispersion functions, and corrected chromaticity were re-measured with low intensity beam $\sim 4E11$ protons per bunch (ppb) to avoid collective effects. These measured optics parameters were well matched with the models [4, 5]. Especially for dispersion, its 1st order of non-linear term was well matched.
- Replacement of the injection kicker system from transmission-line type, which had a serious discharge problem in the vacuum chamber and made extra kicks on circulating beam, to lumped inductance type having low beam coupling impedance [6]. Beam tunings: Injection timing was tuned with observing injection errors and prompt beam losses. Not only DCCT but air-ion-chamber (AIC) loss monitors were used to observe prompt losses [7].
- Two additional RF cavities were installed (totally 8 RF cavities) [8]. Beam tunings: Acceleration time was shortened from 1.9 s to 1.4 s. The beam losses were well controlled during the smoothing acceleration, when most of beam losses happened. The repetition time was changed from 3.2 s to 2.56 s by this April.
- Four skew quadrupoles were newly installed. Their effects to correct the sum resonance were observed [9]. The xy coupling studies were performed with the skew quadrupoles [10].
- Three octupoles were newly installed. Their effects to suppress beam instabilities were observed [11].

The control systems of the skew quadrupoles and the octupoles are going to be ready for user operation in this fall.

Beam Loss Control

The user operation restarted from March 2012, and the beam power was increased with beam commissioning. The beam power was normally limited by beam losses in the collimator area. The dynamic bunch-by-bunch feedback system and the RF feedforward system had strong effects to reduce beam losses [12, 13]. However, there were extra limits of the beam power in several weeks. In mid-April performance of the injection kickers was deteriorated, because matching resistors of the kickers were damaged due to discharge of themselves. To keep beam losses under the acceptable limit, 450 W, the beam power was to be lowered from 190 kW to 100 kW gradually, till the damaged resistors were replaced. Moreover, there was a problem on air-tightness of the tunnel. The beam power had to be limited to 160 kW to reduce radioactive level of exhausted gas from late May to June. Dampers of the air conditioner system were replaced with new ones, which have better air-tightness this summer.

The dynamic bunch-by-bunch feedback system was installed in winter, 2010 to suppress transverse beam instabilities [12]. The system consists of beam position monitors, feedback kickers, and digital signal processing electronics. Stripline exciters, 1.4-m long, are used as the feedback kickers. This system significantly reduced the beam losses during the injection time (0.12 s) and the smoothing acceleration time (0.1 s). For the injected beam of 9E13 ppp, the coherent instabilities could not be suppressed without applying the feedback system, and $\sim 60\%$ of the injected beam was lost during the smoothing acceleration time, though other tunings as patterned sextupoles were already applied. On the other hand, the instabilities were well suppressed for the 9E13 ppp beam with applying the feedback system [4]. A new feedback system is under development to suppress head-tail instabilities [14].

The RF feedforward system was installed to MR at the end of May 2012 to compensate the beam loading effects of the acceleration harmonic and its neighbour harmonics [13]. Applying this system, longitudinal oscillation growth during the smoothing acceleration were suppressed, and the beam losses at the arc of MR were significantly reduced during the smoothing acceleration. The beam power was increased from 190 kW to 200 kW without increasing beam losses, after applying the RF feedforward system.

Besides tunings with the above two systems, ordinal commissioning tunings were performed. The key issues to control the beam losses were to suppress the tune shift during the smoothing acceleration, to tune chromaticity correction, and to adjust the ring collimator positions. Tune shift happened at the beginning of acceleration, though the ripples of main magnets were suppressed with linearizers [15]. The tune shift was caused by the tracking errors of quadrupole fields, but was able to be suppressed by applying patterned currents to the quadrupoles (Fig. 3). Thus to keep optimal tune became easy. The corrected

chromaticity, $\Delta v/(dp/p)$, was controlled from -1 to -5 in order to suppress coherent instabilities coming from the resistive wall impedance of stainless steel vacuum chamber or the impedance at the kickers. The optimal corrected chromaticity depends on protons per bunch, the acceleration time, and ON/OFF of the RF feedforward system. The ring collimators were set 63 pi mmmrad horizontally and 80 pi mmmrad vertically in order to control the beam losses localized within the collimator area.

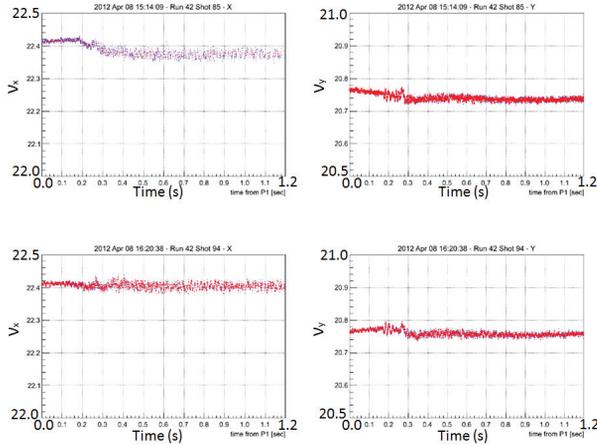


Figure 3: Measured MR tune with the tune meter from the 1st injection. Left side figures are for horizontal tune, and right side figures are for vertical tune. Upper figures are the tunes for non-patterned quadrupoles, and lower figures are the tunes for patterned quadrupoles. The tunes were shifted at the beginning of the acceleration 0.17 s ~ 0.27 s after the 1st injection.

Monitors: New Observation since 2010

In the high power operation, to measure the order of 0.1% beam losses is required to control the residual activations. The DCCT in the MR, which is used to count protons per pulse, has step response proportional to the step size. The step response leads to count less lost protons at each injection. To reduce the systematic error from the deviation in the step response, digital filter was applied [16]. On the other hand, for the prompt losses within 1~2 turns after the injections, the AIC loss monitors were used qualitatively. The prompt losses need to be observed to tune the injection kicker parameters and to get first sign of the deterioration of the injection kickers. AIC monitors were also set in 3-50BT. They were already calibrated, and were used to measure beam halos of the beam from RCS [7].

210 kW Test Operation

The maximum beam power demonstrated with acceptable beam losses was 213 kW. Figure 4 shows the time structure of protons per pulse at the time. There were 4 time injections of 2 bunches from RCS with each 40 ms interval. Totally the 8 bunches, 1.14E14 ppp, were extracted at 30 GeV. Figure 5 shows the integrated signals from the beam loss monitors (BLM) at the same shot. The

BLM address numbers cover the whole ring of the MR. The sensitivity of the BLMs in the collimator area (red area) is set in 1/11 of the ones in the other area (blue area). Figure 6 shows the mountain plot of the BLM signal at the same shot. The time structure starts from the first injection time. The color scale is shown in the right side. The beam losses of the 213 kW operation were localized at the collimator area and at the injection time. The large signal at the extraction in the BLM address 160 to 170 does not mean beam losses but reflected signals from the abort beam dump. Several shots under the same conditions made almost the same amount of losses. In 210 kW operations the beam losses can be localized at the collimator area and the loss powers were from 410 W to 520 W.

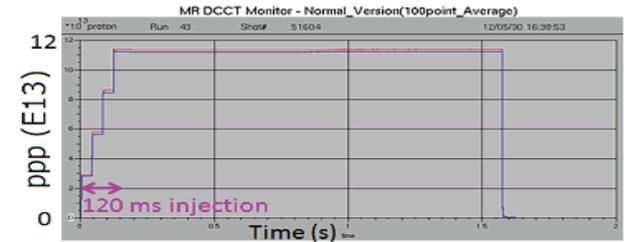


Figure 4: The measured ppp with the DCCT in the 213 kW operation.

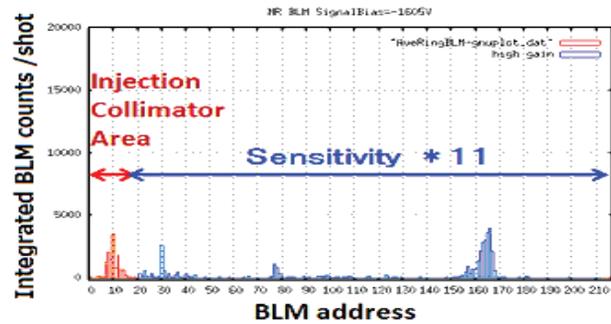


Figure 5: Integrated BLM counts in the 213 kW operation.

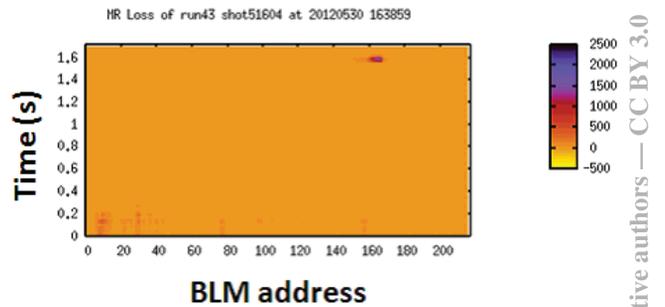


Figure 6: Mountain plot of BLM counts in the 213 kW operation.

Beam Dynamic Simulations

The beam dynamics simulations of the MR were performed with the SAD code [17] and the SCTR code [18]. The modelled injection beams were the RCS simulation results [19] with the SIMPSONS code [20].

Several benchmarks were performed. Simulated beam profiles at the end of the injection time reproduced the features of measured beam profiles, where the sum resonance effects and space charge effects are shown [21]. The bunching factors of the 200 kW operations were well reproduced by simulations. Figure 7 shows the bunching factor of the first 10 ms from the injection. The red line is the measured bunching factor, and the blue line is the simulated one. The conditions were the kinetic energy 3 GeV and the RF voltage 135 kV. Both the bunching factors showed the same periods. Table 1 shows the survival ratio comparison at 60 ms after the injection in 3 GeV. The simulated survival ratio differs 0.5% from the measurement, but the difference is within the shot by shot.

Table 1: Measured vs. Simulated Survival Ratio after the First 60 ms at 3 GeV in the 200 kW Operation

Measurement	0.992 ± 0.002
	(shot by shot)
Simulation	0.988

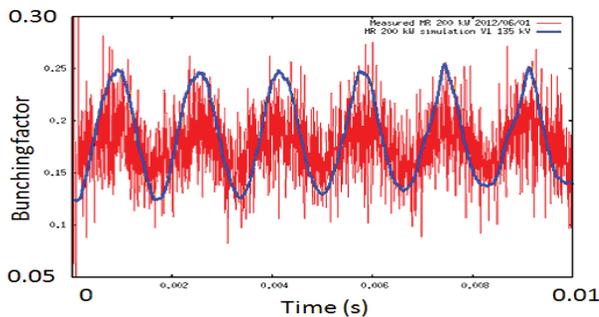


Figure 7: Bunching factor of the first 10 ms at 3 GeV in the 200 kW operation.

Effect of 2nd Harmonic RF

Beam losses can be reduced with using fundamental harmonic RF cavities ($h=9$) and 2nd harmonic RF cavities ($h=18$), because space charge effect is mitigated by modifying the longitudinal bunch shape and increasing the bunching factor. Figure 8 shows the measurements of the wall current monitor signals, the longitudinal mountain view plots and the bunching factors in the case of the fundamental harmonic RFs only and in the case of the fundamental and the 2nd harmonic RFs. The upper figures are for the fundamental harmonic RF, and the lower figures are for the fundamental and the 2nd harmonic RFs, where the voltage ratio $V_2/V_1=70\%$ at the RCS extraction and $V_2/V_1=65\%$ at the MR injection. By using the 2nd harmonic RFs, the local minimum of the bunching factor was increased from 0.15 to 0.25, and the bunch length was stretched from 150 ns to 250 ns. The 250 ns bunch length had no margin for the current injection system, considering that the rise time of the injection kickers is ~ 350 ns and RF bucket length is 598 ns. The bunch length can be longer for higher intensity.

Thus, the magnet power source and the pulse forming networks of the injection kickers are planned to be upgraded, to shorten the rise time [22]. Figure 9 shows time structures of the simulated 98% beam emittances in 3 GeV DC for the fundamental harmonic RFs only ($V_1=135$ kV, $V_2=0$) case and for the fundamental and 2nd harmonic RFs case ($V_1=140$ kV, $V_2=91$ kV). The time starts from the injection. With using the 2nd harmonic RFs the emittance growth can be suppressed horizontally and vertically. After loading the 9th RF cavity [8], beam commissioning with using the 2nd harmonic RFs are scheduled this year.

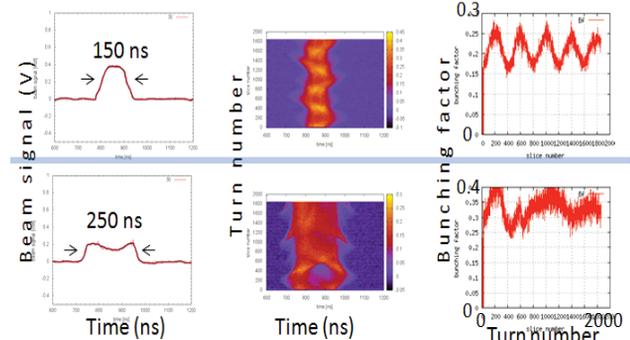


Figure 8: Wave form, WCM and bunching factor. Upper figures are for fundamental RF only, and lower figures are for adding second harmonic RF.

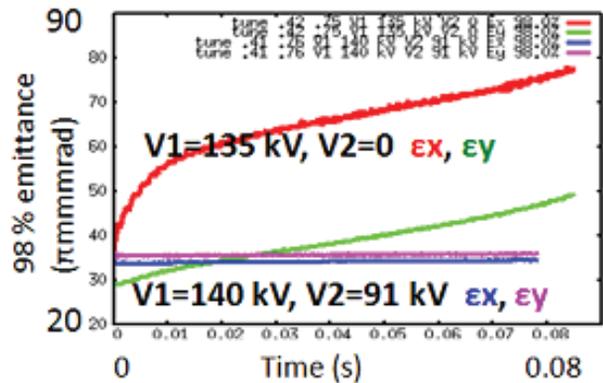


Figure 9: Growth of 98% emittance for fundamental RF only ($V_1=135$ kV, $V_2=0$; red for horizontal, green for vertical), and for adding second harmonic RF ($V_1=140$ kV, $V_2=91$ kV; blue for horizontal, violet for vertical).

Operation Summary and Upgrade Plan in the Near Future

The operation summary from January 2011 to summer 2013 is shown in Table 2. In summer 2013, the J-PARC linac will be upgraded from 181 MeV to 400 MeV, and the beam quality and intensity from the RCS are going to be improved. The beam power of the MR can be reached to 450 kW under the 2.4 s repetition, using the current power supplies of the main magnets [23]. As a further upgrade scenario, 1 s repetition is planned to reach 750 kW, the designed power. This higher repetition scenario differs from our original scenario with 50-GeV extraction. Considering magnetic field saturation and electric power

costs, to keep 30-GeV extraction and to increase the repetition frequency are the reasonable scenario. To achieve the 1 s repetition, the new power supplies of the main magnets are under development [24], and the high field gradient RF cavities with FT-3L cores are to be installed [25].

Table 2: Operation Summary of J-PARC MR

Term	Beam Power	Improvements
2011.1 – 3	145 kW	Bunch by bunch feedback
2011.3 – 11	Shutdown	Ring collimator shields 7 th and 8 th RF system New injection kicker
2011.12 - 2012.6	100-200 kW (RCS 300 kW eq.)	Cycle: 3.2 to 2.56 s Beam loading compensation
2012.7 – 9	Shutdown	Ring collimator upgrade 0.45 to 2 kW 9 th RF system
2012.10 - 2013.7	Over 200 kW (RCS 300 - 400 kW eq.)	Cycle: 2.48 to 2.4 s Second harmonic cavities

The optics in our operation was the same as the original, which is common between the FX mode and the SX mode. The operation point was optimized, but was not far from the designed one, estimated without the actual imperfection. To seek higher intensity, however, we may change optics for the FX mode, because the FX mode does not need to have large peaks of beta functions at the edge of the straight sections, which are utilized for the SX mode.

SUMMARY

The optics parameters of J-PARC MR were re-measured and corresponded with the models well, after the re-alignment in 2011. The maximum beam power delivered to the neutrino target was 200 kW by June 2012. To reduce beam losses, the bunch-by-bunch feedback system and the RF feedforward system were key issues. The upgrade plan in the near future is based on the higher repetition, the collimator upgrade, and the 9th RF cavity that enables us to use the 2nd harmonic RF.

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