RECENT PROGRESS OF J-PARC MR BEAM COMMISSIONING AND OPERATION

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Abstract

The main ring (MR) of the Japan Proton Accelerator Research Complex (J-PARC) has been providing 30-GeV proton beams for elementary particle and nuclear physics experiments since 2009. The beam power of 415 kW has been recently achieved with 2.15×10^{14} protons per pulse and the cycle time of 2.48 s for the neutrino oscillation experiment. Main efforts in the beam tuning are to minimize beam losses and to localize the losses at the collimator section. Recent improvements include the 2nd harmonic rf operation to reduce the space charge effect with a larger bunching factor and corrections of resonances near the operation setting of the betatron tune. Because the beam bunches were longer with the 2nd harmonic rf operation, the injection kicker system was improved to accommodate the long bunches. We plan to achieve the target beam power of 750 kW in JFY 2018 by making the cycle time faster to 1.3 s with new power supplies of main magnets, rf upgrade and improvement of injection and extraction devices. The possibility of the beam power beyond 750 kW is being explored with new settings of the betatron tune.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) consists of the high intensity proton accelerators and the experimental facilities to make use of the proton beams [1]. It has three accelerators; a 400 MeV linear accelerator, 3 GeV rapid cycling synchrotron (RCS) and 30 GeV main ring (MR). MR is a synchrotron with the circumference of 1567.5 m and with three-fold symmetry as shown in Fig. 1. The first straight section is for injection devices and beam collimators. The proton beams from RCS are transported through a beam transport line (3-50BT) to MR. The second straight section is for slow extraction (SX) devices to deliver the beam to the hadron hall. The third straight section is for rf cavities and fast extraction (FX) devices to extract the beam to the neutrino beam-line or the beam abort line.

The cycle time is 2.48 s for the FX mode. The beam is extracted in one turn at the top energy to the neutrino oscillation experiment (T2K). For the SX mode the cycle time is 5.52 s with the flattop duration of 2.93 s. Beam spills of 2 s duration are then delivered to elementary particle and nuclear physics experiments in the hadron hall.

The T2K experiment observed the appearance of electron neutrinos from muon neutrinos made from the secondary particles of the high intensity protons [2]. High intensity proton beams are further demanded for the precise measurements of neutrino mixing parameters.

The beam power has been steadily increased as shown in Fig. 2 in the last six years. It was mostly about 390 kW in the operation of Jan. ~ May of 2016 for FX with 2×10^{14} protons per pulse (ppp). The plan to achieve the target beam power of 750 kW is to make the cycle faster from 2.48 s to 1.3 s with 2×10^{14} ppp. A milestone for the number of accelerated protons was therefore reached. Further efforts are being made for higher intensity. The user operation of 415 kW was successful during the last three days.

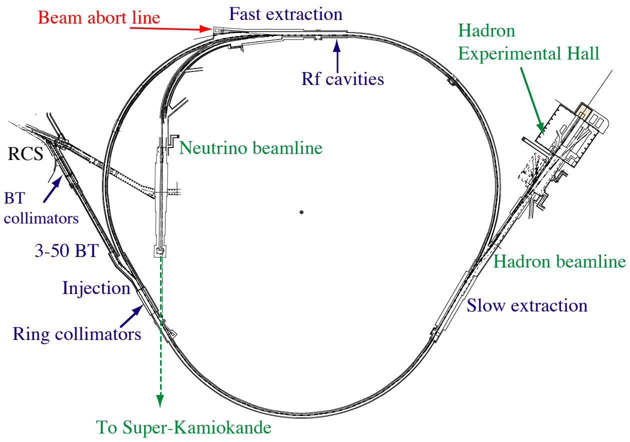

Figure 1: Layout of J-PARC MR.

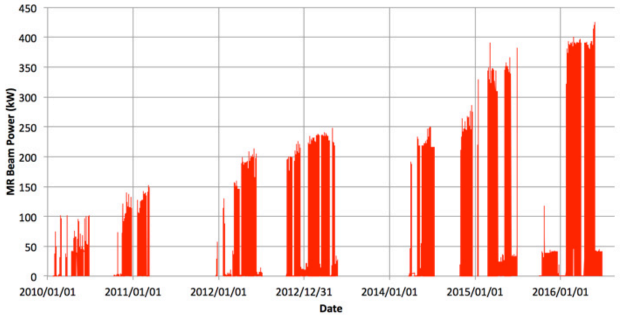

Figure 2: Beam Power Trend Graph.

OPERATION STATUS FOR THE FAST EXTRACTION

Eight bunches of beams are injected to MR in 4 times during the injection period of 0.13 s. The acceleration takes 1.4 s and the accelerated protons are extracted in one turn. The recovery for the magnet currents takes 0.94 s and the total cycle is 2.48 s. Figure 3 shows the beam

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intensity measured with DCCT as a function of the cycle time for a shot of beam power of 416 kW. The number of protons per bunch (ppb) is 2.7×10^{13} at the injection and the number of accelerated protons is 2.15×10^{14} ppp. The beam loss is estimated to be 170 W during the injection period and 417 W during 0.12 s in the beginning of acceleration. The total beam loss is within the MR collimator capacity of 2 kW. The beam loss at 3-50BT is estimated to be 100 W. It is also within the 3-50BT collimator capacity of 2 kW.

The beam loss distribution in the circumference is shown in Fig. 4. The beam loss is measured with beam loss monitors [3] located at all 216 main quadrupole magnets. The gains of the 24 loss monitors (#1 ~ #20 and #213 ~ #216) including the collimator area are set to low, and the others (#21 ~ #212) have higher gain about 8 times. The beam loss is reasonably localized in the collimator area of (#6 ~ #11). Details of the collimator operation are described in Ref. [4].

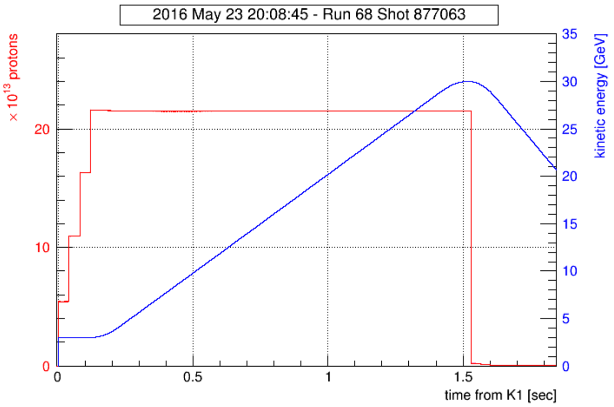

Figure 3: Beam intensity (shown in red) for a user-operation shot of the beam power of 416 kW as a function of the cycle time.

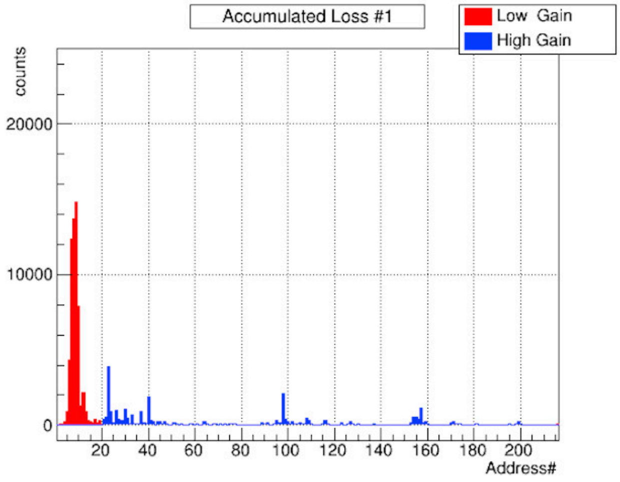

Figure 4: Beam loss distribution measured with beam loss monitors in the circumference as a function of MR address for a shot of the beam power of 416 kW.

RECENT IMPROVEMENTS

Injection Beam Distribution

RCS beam parameters such as painting and operation tune and chromaticity have been intensively explored for high intensity MR operation [5]. Profiles with a low peak should be preferable for reducing the space charge effects. Profiles with little tail should also be preferable for the beam loss reduction. By the RCS beam parameter optimization we managed to have the profiles with parabola distributions, even though the profiles used to be Gaussian distributions. The profile of injection beam is measured with an optical transition radiation monitor (OTR) [6] in 3-50BT (Figure 5).

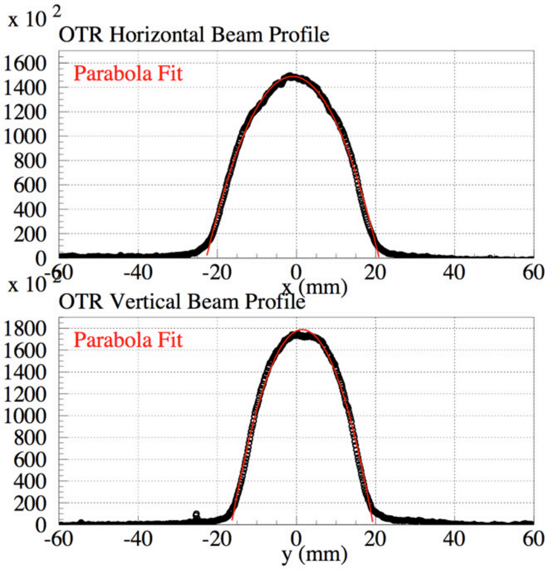

Figure 5: Horizontal beam profile (upper fig.) and vertical beam profile (lower fig.) measured with OTR in 3-50BT.

Rf Pattern

Beam studies with the 2nd harmonic rf indicated the improvement of the bunching factor and beam survival. When the 2nd harmonic rf was set to 0 kV with the fundamental rf of 100 kV, bunching factor was measured to be between 0.2 and 0.3 and the bunch length became about 200 ns. When the 2nd harmonic rf was set to 70 kV with the fundamental rf of 100 kV, bunching factor was improved to be between 0.3 and 0.4 and the bunch length was as long as about 400 ns.

For the recent user operation the fundamental rf of 160 kV and 2nd harmonic rf of 85 kV have been applied during injection period to improve the bunching factor and to reduce the space charge effects. The bunching factor was measured to be about 0.3 during injection period. In the beginning of acceleration the fundamental rf voltage turned up to 280 kV in 60 ms and turned down to 256 kV at 0.4 s after the acceleration start until the acceleration end. The 2nd harmonic rf lasts 0.1 s in the beginning of acceleration and turned off for the rest of acceleration.

Injection Kicker Improvements

The injection kicker system was improved to cope with long bunches for the 2nd harmonic rf operation. The rise time of the injection kicker were improved to be faster with the speed up circuit [7]. The tail was suppressed with the tail matching circuit. There is a reflection pulse that would make an extra kick to a circulating bunch. A compensation kicker was newly installed to cancel the extra kick [8]. It has been used in operation and reduced the beam losses at injections.

Instability Suppression

The chromaticity pattern in the cycle time was optimized to minimize the beam loss. To suppress instabilities, the chromaticity is kept to be negative, typically −6 during injection. If the chromaticity is too small in negative value, instabilities may be observed causing beam losses. If the chromaticity is too large in negative value, we may observe beam losses those are probably due to chromatic tune spread. The optimization is iterated after the change of the beam intensity and parameters of following feedback systems.

A bunch by bunch feedback system has been used to suppress coherent oscillation of each bunch effectively [9]. To suppress internal bunch oscillation, a more wideband feedback system named intra-bunch feedback system [10] is applied during injection and in the beginning of acceleration. The system consists of new stripline BPM's which have wide frequency response, a signal processing circuit and stripline kickers with the bandwidth of 100 kHz ~ 100 MHz. BPM signals are sampled at the rate of 64th harmonic of the RF frequency. The signal processing circuit extracts the betatron oscillation signals on each slice and feedbacks kick signals for each slice. The system has been applied effectively during injection and up to 0.12 s after the acceleration start.

Optics Measurement and Correction

We have recovered the effective physical aperture by corrections of the optics and closed orbit distortion (COD). The stripline kickers and the power amplifiers of the intra-bunch feedback system are used for beta measurement during injection and up to 0.37 s after the acceleration start. The kicker is to excite the betatron oscillation. The amplitudes of the oscillation are then measured with all the BPM's. The square root of beta should be scaled to the oscillation amplitude. The dispersion function is derived from the COD for the momentum deviation of $|\delta| < 1.3\%$. The betatron tune during injection and acceleration is measured from the frequency of the betatron oscillation that is induced by exciters. The results of beta, dispersion and tune are corrected to what we intend to set by adjusting the currents of 11 quadrupole magnet families. Figure 6 shows the horizontal and vertical tunes before and after the optics correction as a function of the cycle time. The tunes after the correction have less deviation from the setting tunes.

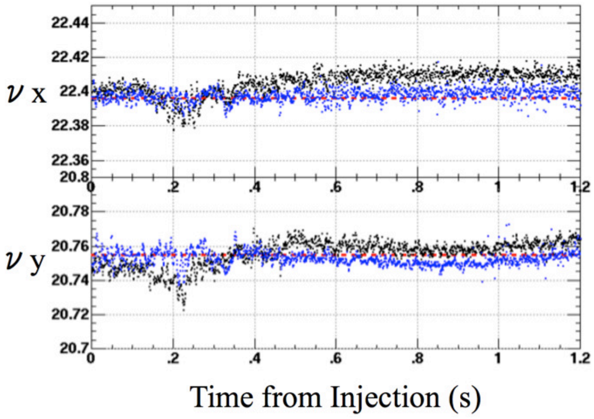

Figure 6: Horizontal tune (upper plot) and vertical tune (lower plot) as a function of the cycle time. Measurements before the optics correction are in black dots and results after the correction are in blue dots. The correction is done up to 0.5 s. The red dashed lines show the setting tunes.

Space Charge Tune Spread

The space charge tune spread was estimated for the beam power of 380 kW. The number of ppb was 2.5× 10^{13} for the cycle time of 2.48 s. The transverse 2 σ emittance was assumed to be 16 π mm mrad and the bunching factor was set to 0.3 based on the measurements. Figure 7 shows the distribution of the tunes of macro particles with the particle tracking simulation program SCTR [11], which takes the space charge effects into account. The operation tune was set to (22.40, 20.75). The tune spread was estimated to be 0.3. There are some resonances of concern, such as a linear coupling resonance $\nu_x + \nu_y = 43$, a half integer resonance $2\nu_y = 41$ and third order resonances.

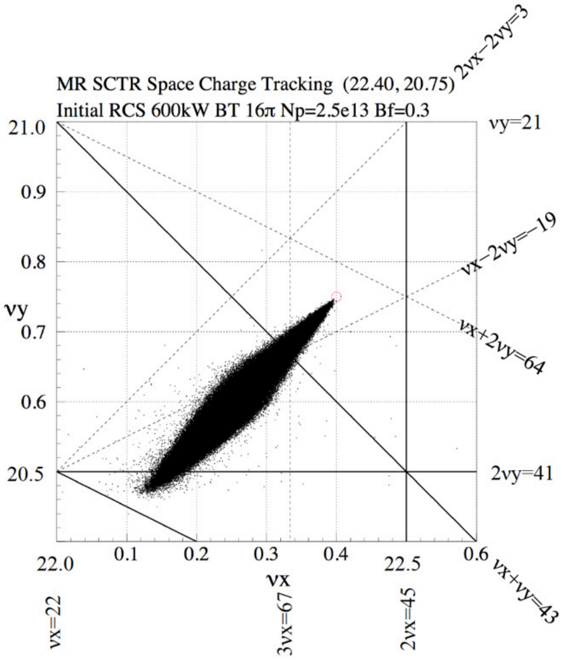

Figure 7: Space charge tune spread and resonances of concern.

Linear Coupling Resonance Correction with Skew Quadrupole Mangets

Rotation errors of the quadrupole magnets and vertical COD at the sextupole magnets cause the linear coupling resonance $\nu_x + \nu_y = 43$. Four skew quadrupole magnets (SQ's) have been used to correct the resonance. Current settings of the SQ's were optimized to recover the beam survival when the tune was set to be (22.28, 20.71) on the resonance for low intensity beams at first [12]. They were further optimized to minimize the beam loss for the high intensity operation. The beam survival has been improved for the beam power of 380 kW equivalent as shown in Fig. 8.

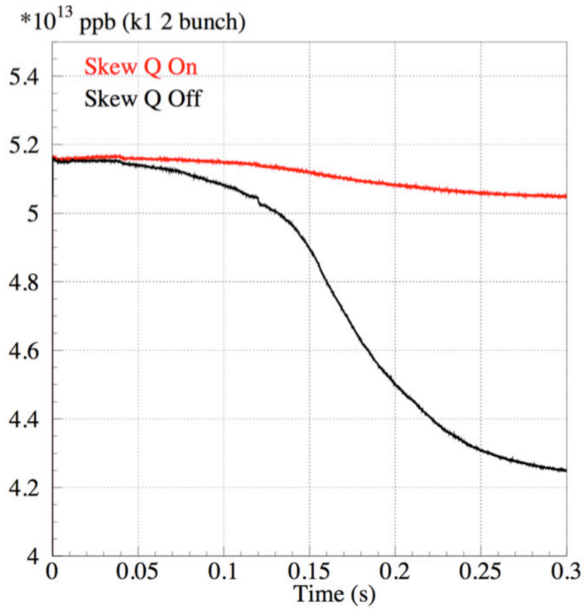

Figure 8: Beam intensity during injection and in the beginning of acceleration for 2-bunch beam for the beam power of 380 kW equivalent with SQ's on (red line) and off (black line).

Half Integer Resonance Correction with Trim Coil of Quadrupole Magnets

The FX septum magnets make undesirable quadrupole fields for circulating beams with the leak fields. They were measured for all 8 FX septum magnets. The sum of the strength K1 corresponded to 3 % of a main quadrupole magnet. Correction currents for the trim coils of three quadrupole magnets near the FX septum magnets were calculated. The correction has been applied and optics were measured at (22.19, 20.54) near the half integer resonance of $2\nu_y = 41$. Improvement of the beta modulation was then observed with the correction.

Third Order Resonance Corrections with Trim Coils of Sextupole Magnets

Third order resonances of $\nu_x + 2\nu_y = 64$ and $3\nu_x = 67$ have been corrected with trim coils of four sextupole magnets. The current setting of trim coils of two sextupole magnets was optimized to recover the beam survival for low intensity beams when the tune was set (22.42, 20.78) on the 3rd order resonance of $\nu_x + 2\nu_y = 64$. The resonance strength $G_{1,2,64}$ expressed by Eq. (1) was then derived from the measurement.

$$G_{1,2,64} = \frac{\sqrt{2}}{8\pi}\beta_x^{1/2}\beta_y k_2 \exp[i(\phi_x + 2\phi_y)] \tag{1}$$

The same procedure was repeated when the tune was set (22.34, 20.75) on the 3rd order resonance of $3\nu_x = 67$. The resonance strength $G_{3,0,67}$ expressed by Eq. (2) was also derived.

$$G_{3,0,67} = \frac{\sqrt{2}}{24\pi}\beta_x^{3/2} k_2 \exp[i(3\phi_x)] \tag{2}$$

Trim coils of four sextupole magnets were used to correct both of $\nu_x + 2\nu_y = 64$ and $3\nu_x = 67$. A solution was solved for a simultaneous equation to reproduce the two resonance strengths in the complex planes as shown in Fig. 9 and 10. It was applied for the high intensity operation and the beam loss was improved.

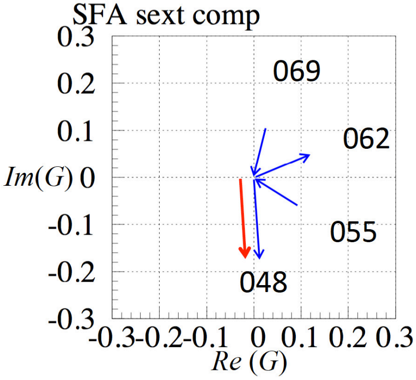

Figure 9: Each contribution of SFA magnets for resonance strength of $\nu_x + 2\nu_y = 64$ in the complex plane at the tune of (22.33, 20.83) with the trim coil correction of SFA048 of +1.1 A (red vector) and with the trim coil correction of four sextupole magnets; SFA048 +1.11 A, SFA055 −0.69 A, SFA062 +0.81 A, SFA069 −0.69 A (blue vectors).

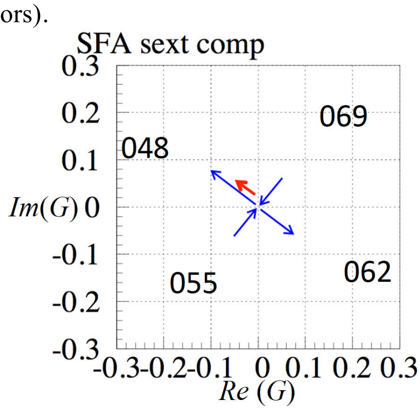

Figure 10: Each contribution of SFA magnets for resonance strength of $3\nu_x = 67$ in the complex plane at the tune of (22.33, 20.83) with the trim coil correction of SFA048 of +0.3 A (red vector) and with the trim coil correction of four sextupole magnets; SFA048 +1.11 A, SFA055 −0.69 A, SFA062 +0.81 A, SFA069 −0.69 A (blue vectors).

OPERATION WITH THE BETATRON TUNE OF (21.35, 21.43)

We have explored the possibility of operation with the other betatron tunes. So far the operation tune was (22.40, 20.75), where we observed a serious linear coupling sum resonance of $\nu_x+\nu_y=43$ within the space charge tune spread. We have searched the area of 21.0 ~ 21.5 for both horizontal and vertical tunes, where there is no linear coupling sum resonance as shown in Fig. 11. Detail search was done and the tune setting of (21.35, 21.43) was the best for the beam survival. The quadrupole field of the FX septum magnets and the third order resonances of $\nu_x+2\nu_y=64$ and $3\nu_x=64$ were corrected. The linear coupling difference resonance of $\nu_x-\nu_y=0$ was corrected with the SQ's. Further the currents of two octupole magnets were optimized to minimize the beam loss. The rf voltage pattern was same as the operation of (22.40, 20.75) described in the preceding section. The parameters of the bunch by bunch and intra-bunch feedback systems were adjusted for the new tune. The chromaticity was set to be −7. We have tested shots of the beam power of 440 kW. The beam loss during injection was 443 W and loss in the beginning of acceleration was 795 W. The sum of the losses was within the MR collimator limit. But it was higher than the loss in the normal operation and should be reduced.

The compensation kicker was not ready to use, because the phase advance between the injection kicker and the compensation kicker was not appropriate for the new tune setting. Changing the polarity of the compensation kicker is a solution and the beam loss reduction is expected. It will be tested in the next available study time.

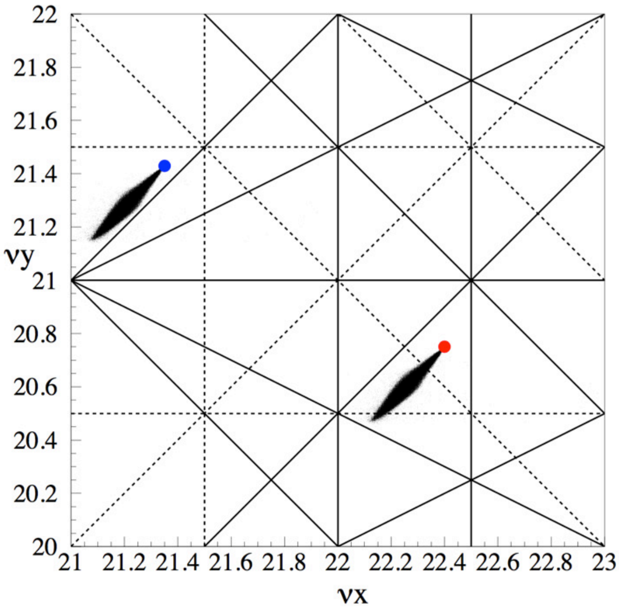

Figure 11: Structure resonances of up to 3rd order (solid lines) and non-structure resonances of half integer and linear coupling resonances (dashed lines). Space charge tune spread shown for the tune of (22.40, 20.75) and (21.35, 21.43) for the beam power of 380 kW.

UPGRADE PLAN FOR THE BEAM POWER OF 750 kW AND MORE

We plan to make the cycle time faster from 2.48 s to 1.3 s to achieve the beam power of 750 kW. The power supplies of main magnets are being upgraded by JFY 2018 [13]. The construction of three new buildings is planned for the power supplies. The rf cavities are also being upgraded for the faster cycling [14]. Additional collimators are being considered to upgrade for the total power capability of 3 kW [4]. The kicker magnets for injection and extraction are being improved and the septum magnets for injection [15] and extraction [16] are upgraded for the faster cycling.

SUMMARY

The beam power of 415 kW has been recently achieved from J-PARC MR with 2.15×10^{14} ppp and the cycle time of 2.48 s for the neutrino oscillation experiment. The beam loss was observed to be 600 W mostly localized at the collimator section. Recent improvements include the 2nd harmonic rf operation to reduce the space charge effect with a larger bunching factor and corrections of resonances near the operation setting of the betatron tune. We plan to achieve the target beam power of 750 kW in JFY 2018 by making the cycle time faster to 1.3 s with new power supplies of main magnets, rf upgrade and improvement of injection and extraction devices. The possibility of the beam power beyond 750 kW is being explored with new settings of the betatron tune.

REFERENCES

[1] Y. Yamazaki et al, "Accelerator Technical Design Report for J-PARC", http://hadron.kek.jp/~accelerator/TDA/tdr2003/index2.html.

[2] K. Abe et al (T2K collaboration), "Observation of Electron Neutrino Appearance in a Muon Neutrino Beam", *Phys. Rev. Lett.*, 112, 061802, Apr. 2014.

[3] T. Toyama et al, "Beam Diagnostics at the First Beam Commissioning of the J-PARC MR", in *Proc. PAC09*, Vancouver, BC, Canada, Nov. 2009, paper WE4GRC01, pp. 1964-1966.

[4] M. Shirakata et al, "New Arrangement of Collimators of J-PARC Main Ring", in *this conference*, paper THAM4Y01.

[5] H. Hotchi et al, "1-MW Beam Operation Scenario of the J-PARC 3-GeV Rapid Cycling Synchrotron", *JPS (The Physical Society of Japan) Conf. Proc.*, vol. 8, 012013, Sep. 2015.

[6] Y. Hashimoto et al, "Two-Dimensional and Wide Dynamic Range Profile Monitor Using OTR / Fluorescence Screens for Diagnosing Beam Halo of Intense Proton Beams", in *Proc. HB2014*, East Lansing, MI, USA, Nov. 2014, paper TUO2AB04, pp. 187-191.

[7] T. Sugimoto et al, "Upgrade of the Injection Kicker System for J-PARC Main Ring", in *Proc. IPAC2014*, Dresden, Germany, Jun. 2014, paper MOPME069, pp. 526-528.

[8] T. Sugimoto et al, "Performance of the Compensation Kicker Magnet for J-PARC Main Ring", in *Proc. IPAC2016*, Busan, Korea, May 2016, paper THPMW021, pp. 3588-3590.

ISBN 978-3-95450-178-6

[9] Y. Kurimoto et al, “The Bunch by Bunch Feedback System in the J-PARC Main Ring”, in *Proc. DIPAC2011*, Hamburg, Germany, May 2011, paper TUPD74, pp. 482-484.

[10] K. Nakamura et al, “Intra-bunch Feedback System for the J-PARC Main Ring”, in *Proc. IPAC2014*, Dresden, Germany, Nov. 2014, paper THOAA03, pp. 2786-2788.

[11] K. Ohmi, et al., “Study of Halo Formation in J-PARC MR”, in *Proc. PAC07*, Albuquerque, NM, USA, Jun. 2007, paper THPAN040, pp. 3318-3320.

[12] J. Takano et al, “Linear Coupling Resonance Correction of the J-PARC Main Ring”, *JPS Conf. Proc.*, vol. 8, 012022, Sep. 2015.

[13] Y. Morita et al, “Development of the J-PARC Main Magnets Power Supplies for High Repetition Operation”, *JPS Conf. Proc.*, vol. 8, 012006, Sep. 2015.

[14] M. Yoshii et al, “Status of the J-PARC Ring Rf Systems”, in *Proc. IPAC2014*, Dresden, Germany, Jun. 2014, paper THPME062, pp. 3376-3378.

[15] T. Shibata et al, “The Development of a New High Field Injection Septum Magnet System for Main Ring of J-PARC”, in *Proc. IPAC2016*, Busan, Korea, May 2016, paper TUPMR039, pp. 1337-1339.

[16] T. Shibata et al, “The Development of a New Low Field Septum Magnet System for Fast Extraction of Main Ring of J-PARC”, in *Proc. IPAC2016*, Busan, Korea, May 2016, paper TUPMR040, pp. 1340-1342.