ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOYPLM1

CHALLENGES TO HIGHER BEAM POWER IN J-PARC: ACHIEVED PERFORMANCE AND FUTURE PROSPECTS

S. Igarashi†, for the J-PARC Accelerator Group, KEK/J-PARC Center,
319-1195 Tokai, Naka, Ibaraki, Japan

Abstract

The Japan proton accelerator research complex (J-PARC) is a world leading intensity frontier accelerator facility, consisting of a 400-MeV H^- linac, a 3-GeV Rapid Cycling Synchrotron (RCS) and a 30-GeV slow cycling Main Ring Synchrotron (MR). The RCS delivers a 530-kW beam with 4.5×10^{13} particles per pulse (ppp) to the Materials and Life science experimental Facility (MLF) in the recent operation. A stable one-hour operation of the design beam power of 1 MW was successfully demonstrated. The construction of the second target station of the MLF with beam power upgraded to 1.5 MW is now under discussion. The MR delivers proton beam to the long-baseline neutrino oscillation experiment, T2K, by fast extraction (FX) and to the hadron experimental hall by slow extraction (SX). For the FX, the maximum beam power is 500 kW and 2.6×10^{14} ppp, the world highest ppp in synchrotrons, and for the SX 51 kW and 5.5×10^{13} ppp with an extremely high extraction efficiency of 99.5 %. The T2K experiment demands the upgrade of the beam power to 1.3 MW. The operation of higher repetition rate is planned with upgrade of hardware such as the magnet power supplies and RF system.

INTRODUCTION

The Japan proton accelerator research complex (J-PARC) comprises high intensity accelerators and facilities to use the secondary beams [1, 2]. H^- beams are accelerated to 400 MeV by the linac and injected to the rapid cycling synchrotron (RCS). The beams are charge exchanged to proton beams during the injection process and accelerated to 3 GeV.

Most of the 3-GeV beams are delivered to the production target of neutron and muon in the materials and life science experimental facilities (MLF). In MLF, twenty of the neutron beam lines are in operation for the various scientific researches including the fundamental physics and industrial uses. For the future upgrade, the construction of the second target station of the MLF is being discussed with the beam power upgrade.

A part of the RCS beams is also delivered to the main ring (MR) and then accelerated to 30 GeV. The beam is provided to either the hadron experimental hall or the neutrino facility. In the hadron hall, the secondary beams such as pions, Kaons and muons, are produced and used for the experiments of the nuclear and elementary particle physics. Upgrade plan is under discussion for the extension of the experimental hall.

† susumu.igarashi@kek.jp

The 30-GeV beam delivered to the neutrino facility are utilized to produce the neutrino beam for the long baseline neutrino oscillation experiment (T2K) with the far neutrino detector Super-Kamiokande which is a 50-kTon water Cerenkov detector located 295 km away from J-PARC. Significant experimental achievements have been reported about the first result on CP (charge conjugation - parity) violation search obtained from the T2K experiment [3]. The result indicates a potential discovery in the near future and further motivates MR to provide higher intensity beams. There is an upgrade plan of building the new far detector Hyper-Kamiokande which will be a 260-kTon water Cerenkov detector.

At the beam tunings of high intensity accelerators, it is necessary to minimize the beam losses. Hands-on maintenances would then be possible with a reasonably low level of radiation doses. Efforts of the beam loss reduction in the J-PARC accelerators are introduced in this paper.

LINAC

The linac consists of an H^- ion source, a Low Energy Beam Transport Line (LEBT), a 324 MHz 3 MeV RFQ and a Medium Energy Beam Transport Line (MEBT1). After the front end, a Drift Tube Linac (DTL) accelerates the beam to 50 MeV followed by a Separated-type DTL (SDTL) up to 191 MeV. A major upgrade was performed in the summer of 2013 for the beam energy of 400 MeV by a series of annular coupled structures (ACS) operating at 972 MHz [4].

The ion source and RFQ was replaced in 2014 for the higher beam current from 30 mA to 50 mA. For the recent operation, the beam current is 50 mA. The beam current of 60 mA was achieved for the beam study [5]. The pulse width is 0.5 ms for the typical operation with the repetition of 25 Hz. The pulse width of 0.6 ms was achieved for the beam study.

During the acceleration of H^- beam, intra-beam stripping causes serious beam losses in ACS. The lattice was recently modified from the original design of equipartitioned lattice to the new lattice with the temperature ratio of Txy/Tz = 0.7. The beam loss is reduced by 40% [6]. Transverse optics matching and RF phase scan of all stages are also being done besides the tunings of the ion source, LEBT, RFQ and chopper when it is required.

RCS

The beam of 400 MeV H^- from linac is injected to RCS by a multi-turn process of 0.5 ms in a typical operation. The beam is charged exchanged with a carbon foil at the same time. The beam is then accelerated to 3 GeV with a repetition rate of 25 Hz. The original design beam power is 1

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOYPLM1

MW. To achieve the beam power, it is designed to have the large aperture of 486π mm mrad. The scheme of beam loss localization with collimators are also provided. The lattice is designed to have high transition γ of 9.14 to avoid the beam loss through the transition crossing [7].

The beam power of the recent MLF operation is 530 kW as shown in Fig.1. The power will be increased by carefully confirming the reliability of the neutron production target. A stable one-hour operation of the original beam power target of 1 MW was successfully demonstrated.

The beam loss of 10^{-3} level was achieved with the transverse painting of 200π mm mrad [7]. Unnecessary foil hitting is reduced with the large painting area and the beam loss due to the foil hitting is then reduced. The space charge effect is also mitigated with the large painting area. For further loss reduction, the sextupole magnets are used for the correction of the resonance of $\nu_x - 2\nu_y = -6$ during the early stage of the acceleration of $t < 5$ ms. They are then used for the chromaticity manipulation during the latter stage of the acceleration of $t > 9$ ms to suppress the transverse instability. The tune at the injection was chosen to (6.43, 6.32), for the horizontal and vertical tunes respectively, to avoid the serious betatron resonances. Besides the 2nd harmonic RF operation, the momentum offset was applied for the longitudinal painting to make the beam with a large bunching factor and to reduce the space charge effect [8, 9].

The beam power beyond 1 MW is demanded by the MLF users with the plan of the second target station. The equivalent beam power of 1.2 MW was demonstrated with the linac beam of 60 mA and the painting duration of 0.5 ms for the injection and acceleration up to 1 GeV. It was also demonstrated with the linac beam of 50 mA and the painting duration of 0.6 ms. The upgrade of the RF system is planned for compensation of the beam loading for the 3 GeV acceleration of the beam beyond 1 MW. The beam power of 1.44 MW will then be demonstrated the later in this year with the linac beam of 60 mA and the painting duration of 0.6 ms.

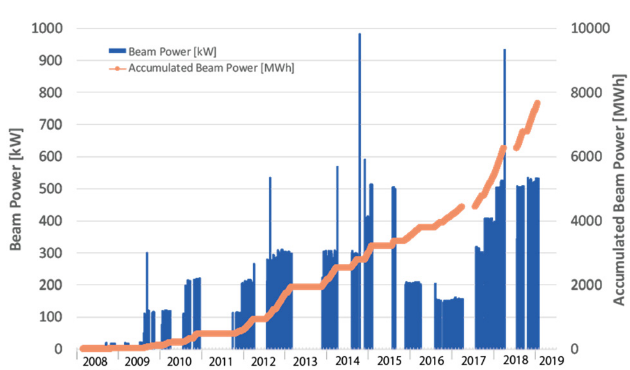

Figure 1: History of MLF beam power and accumulated beam power.

MR

MR receives the two bunches of the beam from RCS every 40 ms in four times. After the injection period of 0.13 s, the beam is then accelerated to 30 GeV in 1.4 s. MR has two operation mode of the extraction: the slow extraction (SX) mode to provide the beam to the hadron experimental hall and the fast extraction (FX) mode for the neutrino facility. Because about 2 s of the beam extraction spill is required for SX, the flat top duration is 2.7 s. The total cycle of SX is 5.2 s. For FX, the beam is extracted in one turn. The cycle time is 2.48 s.

The original design beam power is 750 kW. It is designed to have large aperture of 81π mm mrad. The scheme of beam loss localization with collimators are provided. The lattice is designed to have an imaginary transition γ to avoid the beam loss through the transition crossing. The MR lattice is also designed to have three-fold symmetry.

Slow Extraction

The beam is extracted using a third integer resonance [10]. At the flat top, the resonance is intentionally made with eight resonant sextupole magnets and the tune is gradually moved toward 3vx = 67 with the current pattern of one of the main quadrupole magnet families. The two sets of the electro-static septum (ESS) with the 30μm-thick tungsten ribbons are located at the high beta of 40 m and the dispersion of 0 m. The step size is estimated to be 20 mm. The beam separated by ESS is extracted with the septum magnets (SMS) to the beam line to the hadron hall. The extraction efficiency of 99.5% has been achieved with fine tunings of bump orbit with dynamic bumps, ESS voltages and SMS currents, ESS position and angles, and SMS positions.

The beam power of 51 kW has been achieved for the SX operation. It is so far limited by the capacity of the target in the hadron hall. The target will be upgraded in this summer for the capacity of 95 kW from 57 kW. The hadron hall experiments prefer uniformity of the beam spill which is evaluated with the spill duty factor. The spill duty of about 50% has been achieved with main quadrupole magnets, the spill feedback system with correction quadrupole magnets (EQ and RQ) and the transvers RF system [11].

The COherent Muon to Electron Transition experiment (COMET) to search for the process of the lepton flavour violation is planned in the hadron hall. It requires the slow extraction of the 8 GeV beam for suppression of the anti-proton production. Besides it requires the sparse bunched beam of more than 1 μs for the signal detection. We then have to fill the beam in every other bucket among nine buckets with the extinction ratio of 10^{-10}. The empty bunch was produced with the RF chopper in linac with the extinction ratio of 10^{-6}. The one bunch acceleration is managed in RCS. The injection kicker timing is shifted for the injection to MR for improvement of the extinction ratio. The required extinction ratio was achieved for the bunches of K1 – K3. Some particles were observed for the rear of K4. We have an idea for the improvement. It will be demonstrated in the next available opportunity [12].

Fast Extraction

For the FX operation the beam is extracted in one turn after the acceleration with the cycle time of 2.48 s. Proton beams with the power of 500 kW at maximum have been

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOYPLM1

delivered to the T2K experiment. Figure 2 shows the beam power of the FX and SX operation since 2010.

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 then extracted immediately. The recovery for the magnet currents takes 0.94 s and the total cycle is 2.48 s. The operation beam power was about 470 kW to 500 kW in the recent run of April and May of 2018. Figure 3 shows the beam intensity measured with DCCT as a function of the cycle time for a shot of beam power of 504 kW. The number of protons per bunch (ppb) was 3.3×10^{13} at the injection and the number of accelerated protons was 2.61×10^{14} ppp.

The beam loss was estimated to be 273 W during the injection period and 385 W during 0.12 s in the beginning of acceleration. The total beam loss was within the MR collimator capacity of 2 kW. The beam loss at 3-50BT was estimated to be 50 W. It was 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 [13] 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. [14].

For the MR beam, RCS parameters have been optimized [15]. The beam is required to have low emittances with less halo to minimize the beam loss at MR. We are able to change the RCS parameters every 40 ms such as painting area, betatron tunes and sextupole fields. The small painting area of 50π mm mrad was applied for the low emittance beam. The tune was chosen to be (6.40, 6.39) to separate the space charge spread from the integer resonance with the correction quadrupole magnets QDT's. The sextupole fields during the early stage of acceleration are set for the small chromaticity values to reduce the chromatic tune spread. The fields are set for the large chromaticity values for the instability damping.

During the injection period of MR, the 2nd harmonic RF is applied for 110 kV with the fundamental RF of 155 kV. The bunching factor is measured to be about 0.3. The working point was selected to be (21.35, 21.43). The space charge tune spread is estimated to be 0.4 for the beam of 3.2×10^{13} protons per bunch (ppb) with the measured beam emittances. There are some resonances of concern, such as a half integer resonance $2\nu_y = 43$ and third order resonances.

The optics have been measured during injection and in the beginning of acceleration. The major error sources of the optics modulation and the half integer resonance $2\nu y = 43$ are the leak fields of the FX septum magnets. They are corrected with the trim coils of the three quadrupole magnets near the septum magnets.

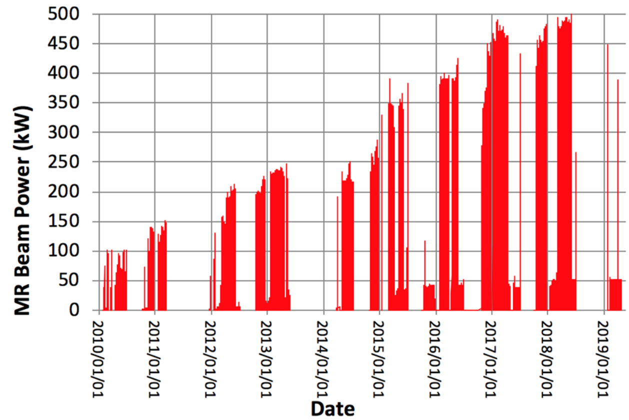

Figure 2: History of MR beam power.

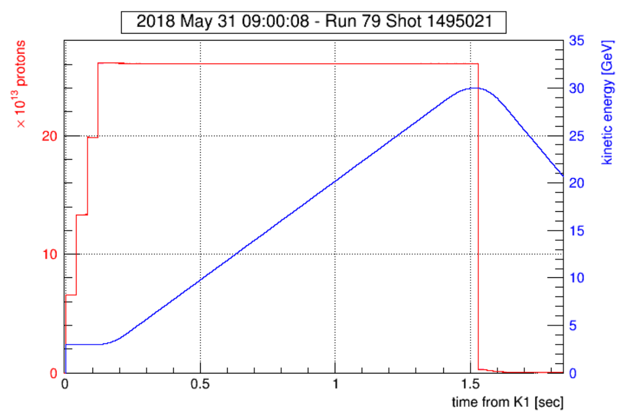

Figure 3: Beam intensity (shown in red) for a user-operation shot of the beam power of 504 kW as a function of the cycle time.

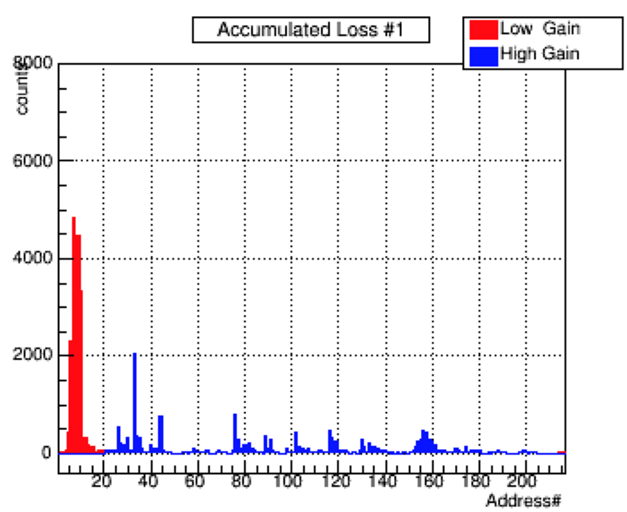

Figure 4: Beam loss distribution measured with beam loss monitors in the circumference as a function of MR address for a shot of the beam power of 504 kW.

Third order resonances of $\nu x + 2\nu y = 64$ and $3\nu x = 64$ 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

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOYPLM1

low intensity beams when the tune was set (21.24, 21.38) on the 3rd order resonance of νx + 2νy = 64. The amplitude of the resonance strength $G_{1,2,64}$ was then measured to be 0.076. The same procedure was repeated when the tune was set (21.33, 21.41) on the 3rd order resonance of 3νx = 64. The amplitude of the resonance strength $G_{3,0,64}$ was also measured to be 0.055. Trim coils of four sextupole magnets were used to correct both of νx + 2νy = 64 and 3νx = 64. A solution was solved for a simultaneous equation to reproduce the two resonance strengths of $G_{1,2,64}$ and $G_{3,0,64}$ in the complex planes. It was applied for the high intensity operation and the beam loss was improved. Further optimization was performed with high intensity beams to reduce the beam losses.

The transverse instability has been observed during injection and the acceleration. It is suppressed with the chromaticity parameters and the intra-bunch feedback system [16].

MR FX UPGRADE PLAN

Concepts

We plan to make the cycle time faster from 2.48 s to 1.32 s to achieve the original design beam power of 750 kW. The required number of accelerated protons is 2.1×10^{14} ppp which we have already achieved. Further upgrade has been promoted to the beam power of 1.3 MW for the CP violation search in the neutrino oscillation processes. The plan is to make the cycle time faster to 1.16 s and the number of the accelerated protons is to be increased to 3.3×10^{14} ppp. Because the accelerated protons of 2.6×10^{14} ppp has been achieved, about 30% of the intensity upgrade is required.

Plan for the Faster Cycling

For the faster cycling of 1.32 s, the magnet power supplies, RF system, injection and extraction devices are being upgraded. The upgrade will be done by JFY 2021.

The electric power supplier does not allow a large power variation of more than 100 MVA that is estimated with the present scheme of main magnet power supplies. Therefore, the energy recovery scheme has been chosen with bank capacitors [17]. Three new buildings were constructed for the power supplies. The new bending magnet power supply for three out of six bending families were installed in the buildings and being tested successfully with the current pattern with the flat top of 2 s. The duration of the flat top is valuable between 0 to 5 s. The cycle time without the flat top is 1.29 s. The faster cycling of 1.16 s will be tested in the near future.

The RF cavities are also being upgraded for the faster cycling [18]. For the cycling of 1.32 s, nine fundamental cavities and two second harmonic cavities are being provided for the required fundamental RF voltage of 510 kV and the second harmonic voltage of 120 kV. For the cycling of 1.16 s, two more fundamental cavities will be added for the required fundamental RF voltages of 600 kV. For the new target of 1.3 MW, the RF anode current power supplies (APS) should be upgraded for the beam loading compensation. The current limit of the present APS is 110 A, which is barely necessary for the loading compensation of the beam of 2.6×10^{14} ppp. It will be upgraded for the current limit of 140 A. It will then be ready for the acceleration of the beam of 3.3×10^{14} ppp.

Additional collimators are being considered to upgrade for the total power capability of 3.5 kW [14]. The kicker magnets for injection and extraction are being improved and the septum magnets for injection [19] and extraction [20, 21] are being upgraded for the faster cycling.

Plan for the Beam Intensity Upgrade

For the high-power beam simulation, transverse profiles of beams from RCS have been measured with multi-ribbon profile monitors (MRPM) at 3-50BT for the intensity of up to 3.8×10^{13} ppb. Based on the measurement, both horizontal and vertical profiles for the simulations were set to be Gaussian distributions with 2σ emittances of 16π mm mrad for beams of 3×10^{13} ppb which was 470 kW equivalent with the cycle of 2.48 s. Emittances of 2σ for both horizontal and vertical distributions were set to be 24π mmmrad for beams of 4×10^{13} ppb which is 1.3 MW equivalent with the cycle of 1.16 s.

The beam tracking simulations were performed with the space charge simulation program SCTR [22] for the beam of 470 kW equivalent with the 2.48 s cycle and the beam of 1.3 MW with the 1.16 s cycle. The simulation result of 470 kW equivalent beam with magnet errors are in good agreement with the measurement. The simulation indicated that the beam of 1.3 MW equivalent would be lost more than 5%, which would not be acceptable for the operation.

The simulation study indicated that the present working point of (21.35, 21.43) was affected by the structure resonances of νx − 2νy = −21 and 2νx − 2νy = 0. We would then search for working points which are not affected by the structure resonances.

Possibilities are being explored with the operation at the working point of (21.40, 20.45), because no low order structure resonances are close to the point as shown in Fig. 5. There is a 4th order structure resonance of 4νy = 81. It, however, should be corrected with the octupole magnets. There is also a 6th order structure resonance 2νx − 4νy = −39. The effect to the beam survival, however, seemed to be small from the simulation. The simulation without magnet errors indicated that the beam of 1.3 MW equivalent would be lost about 2%, which would be acceptable for the operation. Because the simulation result with the magnet errors indicated worse survival, corrections of non-structure resonances, such as νx − νy = 1, should be necessary for the reduction of beam losses. Possibilities are also being explored with the operation at the working point of (22.35, 22.45), because no low order structure resonances are close to the point except for the resonance of 2νx − 2νy = 0.

The beam study for the new possible working points have been performed for the optics measurement and corrections. Further studies of the injection optics matching

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOYPLM1

and resonance corrections of non-structure resonances will be done.

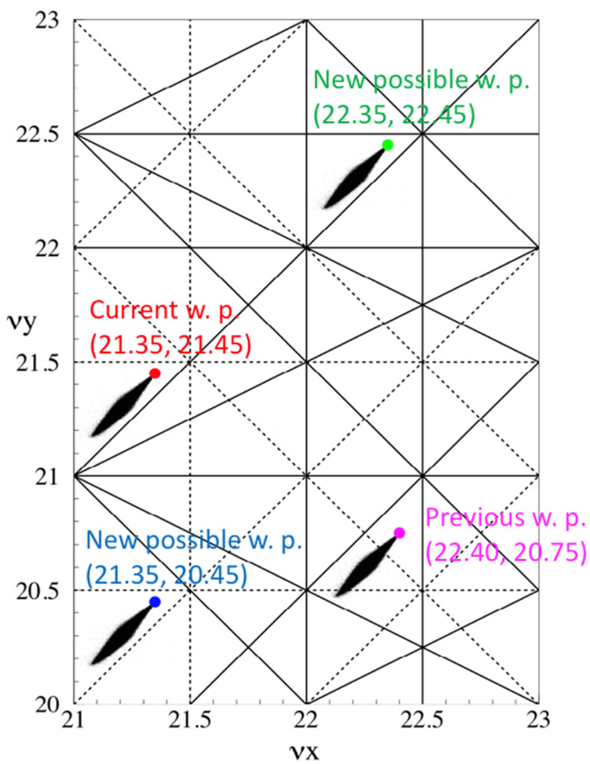

Figure 5: Structure resonances of up to third order (solid lines) and non-structure resonances of half integer and linear coupling resonances (dashed lines). Space charge tune spread shown for the working points of (22.40, 20.75), (21.35, 21.45), (21.35, 20.45) and (22.35, 22.45) for the beam power of 380 kW.

SUMMARY

J-PARC accelerators have been providing high-power beams to the users at the MLF, hadron hall and neutrino facilities who produce significant experimental results. In the linac, the original design current of 50 mA was achieved with the efforts of the beam loss reduction and the acceleration of 60 mA was demonstrated in the beam study. With RCS, the one-hour stable operation of 1 MW was achieved with the loss of 10^{-3} level and the beam power of 1.2 MW was demonstrated in the beam study. The beam power of 1.44 MW will be tested for the upgrade plan. MR delivers the SX beam with the extraction efficiency of 99.5% to the hadron hall with the beam power of 51 kW which is limited by the capacity of the hadron target. The target will be upgraded for the capacity of 95 kW from the present capacity of 57 kW. The proton beam of 8 GeV required for the phase 1 of the COMET muon to electron conversion search experiment was delivered to the hadron hall. For FX operation, MR has recently delivered beams of the power of up to 500 kW with 2.6×10^{14} ppp and the cycle time of 2.48 s for the neutrino oscillation experiment. We plan to achieve the target beam power of 750 kW by making the cycle time faster to 1.32 s with new power supplies of main magnets, RF upgrade and improvement of injection and extraction devices. Further upgrade plan is promoted for the beam power of 1.3 MW with the faster cycling of 1.16 s and intensity upgrade.

REFERENCES

[1] K. Hasegawa *et al.*, "Performance and Status of J-PARC Accelerators", in *Proc. 9th International Particle Accelerator Conference (IPAC'18)*, Vancouver, BC, Canada, Apr.-May 2018, pp. 1038-1040. doi:10.18429/JACoW-IPAC2018-TUPAL017

[2] T. Koseki *et al.*, "Beam Commissioning and Operation of J-PARC Main Ring Synchrotron" *Prog. Theor. Exp. Phys. 2012*, 02B004 2012. doi:10.1093/ptep/pts071

[3] K. Abe *et al.* (T2K collaboration), "Combined Analysis of Neutrino and Antineutrino Oscillations at T2K", *Phys. Rev. Lett.*, 118, 151801, Apr. 2017.

[4] T. Maruta *et al.*, "Recent Progress of the Beam Commissioning in J-PARC Linac", in *Proc. 6th International Particle Accelerator Conference (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3789-3791. doi:10.18429/JACoW-IPAC2015-THPF040

[5] Y. Liu *et al.*, "60 mA BEAM STUDY IN J-PARC LINAC", in *Proc. 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'18)*, Daejeon, Korea, Jun. 2018, pp. 60-63. doi:10.18429/JACoW-HB2018-MOP2WB01

[6] Y. Liu *et al.*, "Commissioning Progress for Power Upgrade of J-PARC Linac", in *Proc. 10th International Particle Accelerator Conference (IPAC'19)*, Melbourne, Australia, May. 2019, TUPTS027.

[7] H. Hotchi *et al.*, "Achievement of a Low-Loss 1-MW Beam Operation in the 3-GeV Rapid Cycling Synchrotron of the Japan Proton Accelerator Research Complex", *Phys. Rev. ST Accel. Beams*, vol. 20, p. 060402, Jun. 2017.

[8] H. Hotchi *et al.*, "Beam Loss Reduction by Injection Painting in the 3 GeV Rapid Cycling Synchrotron of the Japan Proton Accelerator Research Complex", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 040402, Apr. 2012. doi:10.1103/PhysRevSTAB.15.040402

[9] F. Tamura *et al.*, "Longitudinal Painting with Large Amplitude Second Harmonic RF Voltages in the Rapid Cycling Synchrotron of the Japan Proton Accelerator Research Complex", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 041001, Apr. 2009. doi:10.1103/PhysRevSTAB.12.041001

[10] M. Tomizawa, "Status and Beam Power Ramp-up Plans of the Slow Extraction Operation at J-Parc Main Ring", in *Proc. 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'18)*, Daejeon, Korea, Jun. 2018, pp. 347-351. doi:10.18429/JACoW-HB2018-THA1WD03

[11] R. Muto *et al.*, "Current Status of Slow Extraction from J-PARC Main Ring", in *Proc. 10th International Particle Accelerator Conference (IPAC'19)*, Melbourne, Australia, May. 2019, WEPMP007.

[12] M. Tomizawa *et al.*, "8 GeV Slow Extraction Beam Test for Muon to Electron Conversion Search Experiment at J-PARC", in *Proc. 10th International Particle Accelerator Conference (IPAC'19)*, Melbourne, Australia, May. 2019, WEPMP010.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOYPLM1

[13] T. Toyama *et al.*, "Beam diagnostics at the first beam commissioning of the J-PARC MR", in *Proc.* 23rd Particle Accelerator Conf *(PAC09)*, Vancouver, Canada, May. 2009, paper WE4GRC01, pp. 1964-1966.

[14] M. Shirakata *et al*., "New Arrangement of Collimators of J-PARC Main Ring", in *Proc. 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, Malmö, Sweden, Jul. 2016, doi:10.18429/JACoW-HB2016-THAM4Y01.

[15] H. Hotchi *et al*., "Pulse-by-pulse Switching of Operational Parameters in J-PARC 3-GeV RCS", *J. Phys. Conf. Ser. 1067*, p. 052015, 2018, doi:10.1088/1742-6596/1067/5/052015.

[16] K. Nakamura *et al*., "Intra-bunch Feedback System for the J-PARC Main Ring", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, paper THOAA03, pp. 2786-2788.

[17] T. Shimogawa *et al.*, "New Power Supply of Main Magnets for J-Parc Main Ring Upgrade", in *Proc. 10th International Particle Accelerator Conference (IPAC'19)*, Melbourne, Australia, May. 2019, TUPMP016.

[18] C. Ohmori *et al*., "The Second Harmonic RF System for J-PARC MR Upgrade", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 420-422 doi:10.18429/JACoW-IPAC2016-PAPERID MOPMW011.

[19] T. Shibata *et al.*, "The New High Field Injection Septum Magnet System for Main Ring of J-PARC", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 576-578, doi:10.18429/JACoW-IPAC2017-MOPIK034.

[20] T. Shibata *et al.*, "The New Eddy Current Type High Septum Magnets for Upgrading of Fast Extraction in Main Ring of J-PARC", in *Proc. 10th International Particle Accelerator Conference (IPAC'19)*, Melbourne, Australia, May. 2019, TUPTS029.

[21] T. Shibata *et al.*, "The New High Field Septum Magnets for Upgrading of Fast Extraction in Main Ring of J-PARC", in *Proc. 10th International Particle Accelerator Conference (IPAC'19)*, Melbourne, Australia, May. 2019, TUPTS030.

[22] K. Ohmi *et al.*, "Study of Halo Formation in J-PARC MR", in *Proc. 22nd Particle Accelerator Conf. (PAC'07)*, Albuquerque, NM, USA, Jun. 2007, paper THPAN040, pp. 3318-3320.