ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC10

RF SYSTEM UPGRADE FOR 1.3 MW OPERATION OF J-PARC MAIN RING

K. Seiya*, K. Hara, K. Hasegawa, M. Nomura, C. Ohmori,
H. Okita, T. Shimada, Y. Sugiyama, F. Tamura, M. Yamamoto, M. Yoshii
J-PARC Center, JAEA and KEK, Tokai-mura, Ibaraki, Japan

Abstract

The J-PARC Main Ring accelerates proton beam from 3 GeV to 30 GeV and delivers it to T2K long baseline neutrino experiment. In the last two years the beam power was increased from 500 kW to 750 kW by increasing both the beam intensity and the acceleration cycle repetition rate. The T2K detector is scheduled to be replaced by the new Hyper-K detector; the latter will be able to accept a 1.3 MW proton beam by 2028. To achieve 1.3 MW beam power, J-PARC plans to upgrade the Main Ring by further increasing both intensity and repetition rate. The Main Ring uses low frequency, high bandwidth RF cavities with Magnetic Alloy cores, powered by two 600 kW tetrode tubes. Under the upgrade plan, the number of RF cavities will be increased to secure the RF voltage and longitudinal acceptance. The anode power supply will be upgraded to provide enough current for both gap voltage and beam loading compensation. The upgraded LLRF system will be optimized to control fundamental and 2nd harmonic rf voltages, suppress coupled bunch instabilities and compensate beam loading effects. Current operational status as well as details of the upgrade plan and related simulation results will be discussed in this paper.

J-PRAC MR BEAM POWER UPGRADE SCENARIO

Over the past 20 years, the J-PARC Main Ring has delivered a 30 GeV proton beam to the target for the T2K Neutrino experiment. As of November 2023, the beam power has finally reached 750 kW. Looking ahead, J-PARC plans to further increase the power to 1.3 MW for the Hyper-K experiment, which is anticipated to accept the beams in 2028.

To support this plan, the Main Ring will undergo several upgrades over the next five years. The repetition rate will be increased from 1.36 seconds to 1.16 seconds, and the beam intensity will be raised from 2.1×10^{14} protpns per pulse(ppp) to 3.3×10^{14} protons per pulse [1, 2].

STATUS OF THE MR RF SYSTEM FOR 750 kW OPERATION

The proton beam is injected from Rapid Cycle Synchrotron(RCS) and accelerated from 3 GeV to 30 GeV with 9 RF cavities in MR. Two 2nd harmonic cavities reduce the bunching factor for space charge effects at injection energy. The ring is a three folded structure with 1576.5 m circumference including three 116 m long straight sections. Nine fundamental cavities are located in the straight section called Insertion-C, and two second harmonic cavities are in Insertion-A. The power supplies are located in D3 and D1 building respectively. The fundamental RF frequency changes from 1.67 to 1.71 MHz during acceleration.

MA Cavity

MR utilizes MA-loaded cavities to achieve high field gradients [3]. MA core maintains a constant shunt impedance under high magnetic fields without losing it due to high loss effects. In 2016, the core material was upgraded from FT3M to FT3L, doubling the shunt impedance, enabling the shortening of cell length and an increase in gap voltage. Each cavity comprises either three or four cells, with each cell containing six cores and a ceramic gap, totaling a length of approximately 0.5 m, and operating at a maximum voltage of 14 kV per gap. Another advantage of the MA core is its broadband impedance. The Q-value was set to 20 by cutting the core in half and adjusting the gap between the half cores. The measured impedance for fundamental and second harmonic cavities with four cells is shown in Fig. 1.

Following the reassembly and transformation of three 5-gap cavities into 4-gap cavities during the 2023 summer shutdown, the MR now comprises six 4-gap fundamental cavities, three 3-gap fundamental cavities, and two 4-gap second harmonic cavities [4].

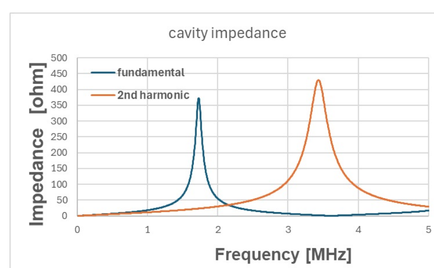

Figure 1: Measured impedance of 4-gap fundamental cavity and 4-gap second harmonic cavity.

Anode Power Supply

The final amplifier utilizes two 600 kW tetrode vacuum tubes to drive each cavity. The anode power supply is constructed using multiple inverter units with IGBT switching devices connected in parallel . The supply output voltage is 10 kV, and the total current depends on the number of units, with 6.7 A per unit.

In summer shutdown 2023, six supplies are extended the the containable number units to 19 by putting additional

* kiyomis@post.kek.jp

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC10

room for the 4 more inverters on top of the power supply. Due to a physical constrain of the power supply building, three of nine anode power supplies can contain maximum 15 units. Currently, 16 units for six 4-gap fundamental cavities, 12 units three 3-gap fundamental cavities, and two 4-gap second harmonic cavities are operated to provide the necessary current for the cavity voltage and compensate for beam loading as plotted in Fig. 2.

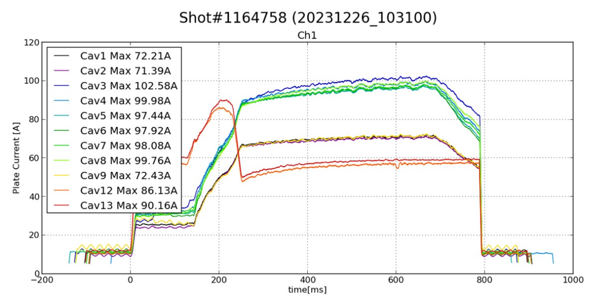

Figure 2: Anode current on each cavity during 760 kW operation.

LLRF

A new LLRF system was developed based on the Micro TCA platform, replacing the old VME system in 2022 [5]. The phase feedback loop suppresses mode 0 dipole oscillations by comparing the phase difference between the wall current monitor signal and the cavity phase reference. The voltage feedback loop measures the gap voltage and mitigates neighbor harmonic modes, the fundamental (h = 6, 7, 8, 10, 11, 12) and the second harmonic (h = 15, 16, 17, 19, 20, 21), with multi-harmonic vector control to suppress coupled bunch instability as shown in Fig. 3.

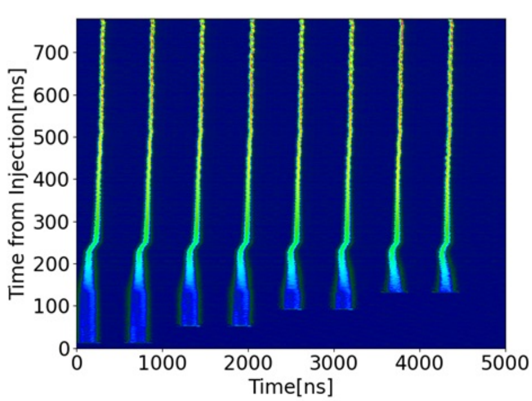

Figure 3: Mountain range plot with wall current monitor signal from injection to extraction.

RF Parameters and Emittance

The RCS injected two bunches, each containing 2.6×10^{13} protons, at 25 Hz, repeating this process four times. Subsequently, all eight bunches were accelerated with the voltage pattern shown in Fig. 4. The harmonic is number of 9 leaving one bucket empty. The wall current monitor signal was recorded during the first quarter of the synchrotron period at injection and utilized for phase space distribution reconstruction with phase space tomography [6, 7]. The root-mean-square (rms) bunch length and momentum distribution from the RCS were measured at 86.9 nsec and 0.0175, respectively, with an emittance of 1.77 eV-sec. The bunch was captured using an RF bucket with fundamental and second harmonic cavities, illustrated in Fig. 5. The bunch length was measured every 1 msec for the bunches until extraction, and the data was plotted in Fig. 6. The last 50 msec of data were utilized to estimate an emittance, assuming a quadrupole oscillation in a stationary bucket with 450 kV, resulting in an emittance of 1.76 eV-sec.

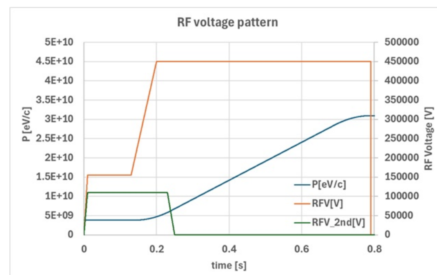

Figure 4: RF voltage patterns for fundamental and second harmonic RF.

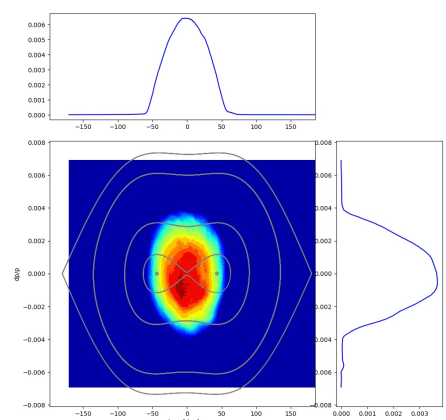

Figure 5: Longitudinal phase space at MR injection with an intensity of 3 E12 protons per bunch.

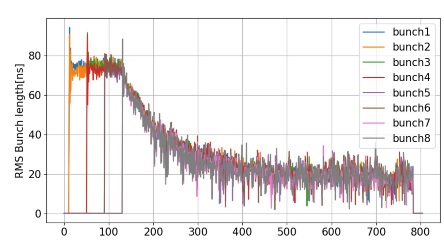

Figure 6: Measured rms bunch length from injection to extraction.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC10

RF REQUIREMENTS FOR THE 1.3 MW OPERATION

The Main Ring RF system will undergo upgrades, including the expansion of power supplies and the addition of cavities. These upgrades are aimed at mitigating beam loading and space charge effects, ensuring stable operation even at higher intensities and repetition rates. In order to decrease the cycle time from 1.36 to 1.16 sec, the acceleration time will be reduced from 0.65 to 0.58 sec.

Required Voltage

The RF voltage requirement was assessed through multi-particle simulations involving three different intensities: 2.0×10^{14}, 2.6×10^{14}, and 3.3×10^{14} ppp at RF voltages of 450 kV, 510 kV, and 550 kV with Beam Longitudinal Dynamics code BLonD [8]. Bunch length and momentum distribution were measured at each turn, and both the bunching factor and momentum filling factor were computed. Figure 7 shows the results with a fixed cycle time of 1.36 sec. To achieve acceleration of 3.3×10^{14} ppp at 1.36 sec repetition rate while ensuring a bunching factor exceeding 0.3 at injection energy and a momentum filling factor below 90 percent without beam loss, the required RF voltage was determined to be 510 kV.

Figure 8 shows the results with different cycle times: 1.36 sec and 1.16 sec, at a fixed intensity of 3.3×10^{14} ppp. The required voltage for 1.3MW operation was established as 510 kV.

To increase the RF voltage from 450 kV to 510 kV, a 4-gap cavity will be constructed in 2024 and operated in 2025. Furthermore, another 4-gap cavity will be installed in 2026 to ensure stable operation with sufficient headroom.

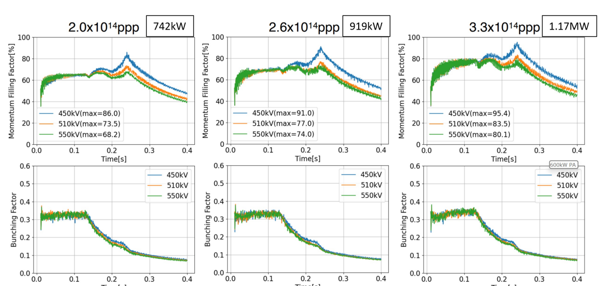

Figure 7: Simulation results of momentum filling factor and bunching factor at 1.36 sec cycle time with three different intensities and RF voltages.

Required Anode Current

The previous study estimated the required anode current to establish gap voltage while compensating for beam loading effects using a phasor diagram [9]. Maximum anode current was measured during 1.36 sec operation at different intensities for all 11 cavities and compared with the calculations, as shown in Fig. 9. The results show that the required anode current for 3.3×10^{14} ppp operation is 129 A for 4-gap fundamental cavities, 93 A for three 3-gap fundamental cavities, and 108 A for 4-gap second harmonic cavities. Additional inverter units will be installed in 2024 and 2025, with the total reaching 19 units for 4-gap fundamental cavities, 14 units for three 3-gap fundamental cavities, and 16 units for 4-gap second harmonic cavities by the end of the summer shutdown in 2025.

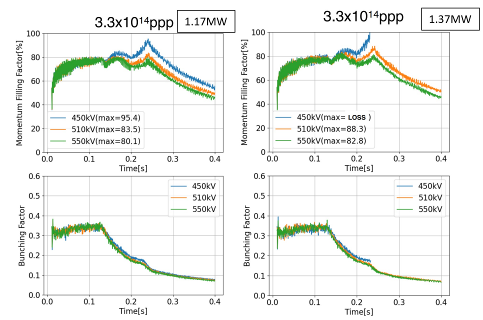

Figure 8: Simulation results of momentum filling factor and bunching factor at intensity of 3.3E14 ppp with two different cycle times:1.36 sec(left) and 1.16 sec(right).

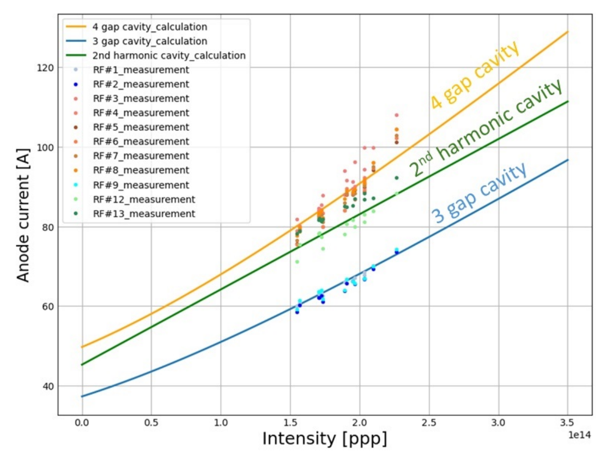

Figure 9: Comparison between estimated anode current and measurements at different intensities on three different cavity types.

CONCLUSION

MR successfully delivered 760 kW for the T2K experiment in November 2023. Following a revisited original RF upgrade plan, it was decided to build three 3-gap cavities and six 4-gap cavities instead of nine 4-gap fundamental cavities. This new configuration provided ample headroom for Anode PS current and facilitated the operation of a 760 kW beam. Our next milestone involves commissioning an 800 kW beam for normal operation and establishing 900 kW in 2024. The RF system upgrade plan appears promising to accommodate the acceleration of 3.3×10^{14} ppp with increased inverter units and cavities by 2025. Subsequently, we have set our sights on achieving 1.3 MW operation after the cycle time was reduced to 1.16 sec.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC10

REFERENCES

[1] "Accelerator Technical Design Report for 1.3 MW Operation at J-PARC Main Ring", KEK Report 2021-2, June 2021.

[2] M. Yoshii *et al.*, "Present status and future upgrades of the J-PARC ring RF systems", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 984–986. doi:10.18429/JACoW-IPAC2018-TUPAK011

[3] Chihiro Ohmori *et al.*, "Development of a high gradient rf system using a nanocrystalline soft magnetic alloy", *Phys. Rev. ST Accel. Beams*, volume 16, pp. 165211, Nov. 2013. doi:10.1103/PhysRevSTAB.16.112002

[4] K. Hasegawa *et al.*, "Status and upgrade plan of the MR Ring RF systems in J-PARC", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2031–2033. doi:10.18429/JACoW-IPAC2022-WEPOTK004

[5] F. Tamura *et al.*, "Commissioning of the next-generation LLRF control system for the Rapid Cycling Synchrotron of the Japan Proton Accelerator Research Complex", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 999, p. 165211, May 2021. doi:10.1016/j.nima.2021.165211

[6] Longitudinal Phasespace Tomography, https://tomograp.web.cern.ch/.

[7] H. Okita *et al.*, "Improvement of the longitudinal phase space tomography at the J-PARC synchrotrons", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 4710–4713. doi:10.18429/JACoW-IPAC2023-THPL105

[8] CERN Beam Longitudinal Dynamics code BLonD. https://blond.web.cern.ch

[9] Y. Sugiyama *et al.*, "Estimation of the anode power supply current of the J-PARC MR RF system for 1.36 s cycle operation", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2320–2322. doi:10.18429/JACoW-IPAC2023-TUPM056