ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK004

STATUS AND UPGRADE PLAN OF THE MR RING RF SYSTEMS IN J-PARC

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Abstract

The J-PARC Main Ring (MR) is a high intensity proton accelerator and delivers 30 GeV proton beams for the long-base line neutrino experiment and the hadron experiments. At present, the beam intensity supplied to the neutrino experiment reached 520 kW with a cycle time of 2.48 s. Toward the design beam power of 750 kW and future goal of 1.3 MW, we chose shortening the MR operation cycle. Accelerating time is shortened in order to shorten the cycle, so a high accelerating voltage is required. Therefore, it is necessary to upgrade the RF systems. This RF upgrade expands the current nine RF systems to a total of thirteen. We are planning to fabricate four RF power sources and add four additional cavities that are recombined with existing cavities. The present status and upgrade plan of the MR RF systems are reported.

INTRODUCTION

The J-PARC facility is a high intensity proton accelerator and consists of a 400 MeV Linac, a 3 GeV rapid cycling synchrotron (RCS) and a 30 GeV main synchrotron (MR). In the MR, injected the proton beams from the RCS are accelerated from 3 GeV to 30 GeV and delivered to the neutrino experiment (T2K) in a fast extraction mode (FX) and to the hadron experimental facility in a slow extraction mode (SX). The current achieved beam power is 510 kW at 2.48-s cycle time in FX and 60 kW at 5.2-s cycle time in SX. In order to achieve the designed beam power of 750 kW and the future target power of 1.3 MW for the Hyper Kamiokande experiment (HK), high repetition cycle in MR was selected. It is planned to replace the main magnet power supplies. In this upgrade plan, the required accelerating voltage for the RF system is 510 kV or higher for the 750 kW and 600 kV or higher for the 1.3 MW. In order to achieve this required voltage, we have developed and mass-produced new magnetic alloy material core (FT3L), which has more than twice the impedance characteristics of the FT3M core that has been used since the beginning of operation [1, 2]. New 4-gap or 5-gap high accelerating field gradient cavities with FT3L cores were also developed [3] and we replaced all nine original 3-gap cavities with FT3M between 2014 and 2016. At present, the 9 RF systems, 7 systems for the acceleration and 2 systems for the 2^{nd} harmonic system, are operating without serious troubles.

MR RF SYSTEM CONFIGURATION

In operation after June 2022, when the magnet power supplies will be replaced, the operation cycle time will be reduced from 2.48 s to less than 1.36 s, and the accelerating time will be reduced from 1.4 s to 0.65 s. As a result, the required accelerating voltage will increase from 280 kV to 510 kV or higher. It is necessary to use all nine existing FT3L cavities as fundamental cavities for acceleration, and two new 2^{nd} harmonic RF systems are required. In addition, to achieve 1.3 MW, the cycle time and accelerating time will be 1.16 s and 0.58 s, respectively. And the required accelerating voltage will be 600 kV or higher. In this case, two more high accelerating field gradient system would be added for a total of 11 accelerating RF systems [4].

Upgrade of Anode Power Supplies

The anode power supply (APS) that supplies power to a final stage amplifier for driving a cavity consists of 15 inverter units and its current limit is 110 A. Figure 1 shows the measured peak anode current of the APS versus the number of circulating protons. The expected maximum number of circulating protons in a APS with 15 inverter units is $2{\times}10^{14}$ protons per pulse (ppp) for a 5-gap cavity and $2.8{\times}10^{14}$ ppp for a 4-gap cavity. At present, beam power of 520 kW in FX mode is now achieved with a $2.7{\times}10^{14}$ ppp at 2.48-s cycle time. The design beam power of 750 kW can be reached at $2{\times}10^{14}$ ppp for a 1.28-s cycle, which is below the current limit of the APS. However, to achieve 1.3 MW, $3.3{\times}10^{14}$ ppp at 1.16-s cycle time is required, which exceeds the APS current limit of 110 A. This requires an increase in the output current capacity of the APS by adding inverter units. For a 4-gap cavity, this can be achieved with the APS with 19 inverters units by adding 4 inverter units (Fig. 2). However, 3 of 9 existing APS cannot add inverters due to the

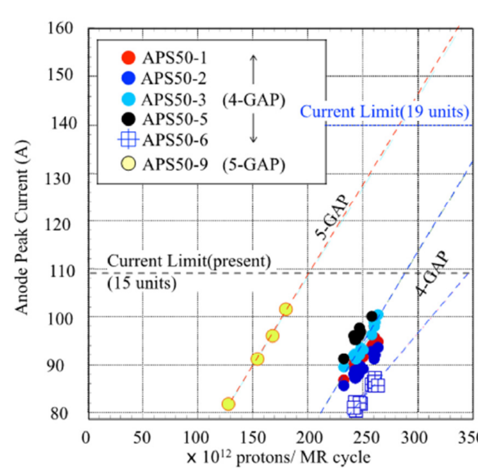

Figure 1: The measured peak anode current of the APS versus the number of circulating protons.

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physical space limitation of the building. The combination of these 3 APSs and 4-gap cavities cannot handle up to 1.3 MW. Therefore, 3 APSs which are limited to 15 inverter units will be used in combination with 3-gap cavities, and remaining 6 APSs that can be expanded with inverter units and 4 newly installed APSs will be used in combination with 4-gap cavities. The power supply will be manufactured and installed 1 system per year, and a total of 4 systems will be installed from 2022 to 2025. Additional inverter units will also be added from 2023.

Figure 2: Anode power supply with 19 inverter units

Upgrade of RF Cavities

Two sets of second harmonic RF systems are needed to achieve the design beam power of 750 kW. In addition, two sets of additional high accelerating field gradient systems are needed to achieve 1.3 MW. Two 2^{nd} harmonic cavities are to be installed in other straight sections (Ins. A) in the MR tunnel. The cavity using the FT3M core used in the previous cavities is also acceptable because there is enough space for installation. Therefore, we reconstructed two 4-gap cavities by using four 3-gap cavities from the previous nine 3-gap cavities that were stored. Reconstruction of the cavities took place in 2018 and 2019, and those two cavities were installed in the MR beamline in 2020. One power supply has been installed and adjusted in May 2022 and is ready for operation (Fig. 3). The other power supply is scheduled for installation in 2023. The RF system configuration of 9 fundamental cavities and two 2^{nd} harmonic cavities for design beam power of 750 kW will be ready for operation at the end of 2023.

The next step toward 1.3 MW is to add two more high field gradient accelerating systems. There is a total of nine highly accelerated gradient cavities with FT3L installed, consisting of seven 5-gap cavities and two 4-gap cavities. However, the 5-gap cavities were limited in beam power increase due to the current limitation of the APS. Therefore, all 5-gap cavities are used as 4-gap cavities with one gap shorted. This means that there are 7 unused acceleration gaps. In addition, 3 APSs that cannot be added to the inverter unit must be used in combination with 3-gap cavities. Therefore, three 3-gap and five 4-gap cavities will be reconfigured from six of the seven existing 5-gap cavities. This recombination work will start in 2023 and is scheduled for three years until 2025. MR RF system configuration is listed in Table 1.

Table 1: MR RF System Configuration

Power [kW]	520	750	1300
$\times 10^{14}$ ppp	2.7	2	3.3
Cycle time [s]	2.48	1.28	1.16
Accl. time [s]	1.4	0.65	0.58
4 / 3* GAP Cavity$_{acc}$			
V_{acc} [kV]	280	510	600
# of Cav. (FT3L)	7	9	8 / 3*
# of INV. units/APS	15	15	19 / 15*
Resonant freq. / Q-value	1.72 MHz / 21		
4 GAP Cavity$_{2nd}$			
V_{2nd} [kV]	110	110	110
# of Cav. (FT3L/3M)	2 / 0	0 / 2	0 / 2
# of INV. units/APS	12	12	15
Resonant freq. / Q-value	3.44 MHz / 14		
upgrade schedule		~ 2023	~ 2025

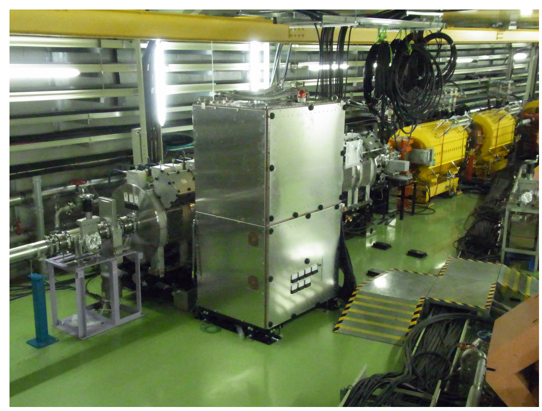

Figure 3: Two 2^{nd} harmonic RF cavities with FT3M. The first of the 2^{nd} harmonic RF cavity is ready for operation. The second one, the cavity was installed and a final stage amplifier will be connected in 2023.

ISSUES FOR STABLE OPERATION

High Frequency Resonances of MR RF Cavities

As the beam intensity has increased, various instabilities have come to be seen. In case of the debunch process of slow extraction operation, the formation of a longitudinal microstructure has been confirmed. The possibility that RF cavities are one of the sources of the microstructure is being considered. To confirm this possibility, the impedance of the 4-gap cavity installed in the MR tunnel was measured in 2019 using the stretched wire method [5]. Figure 4 shows the measured impedance versus frequency up to 1 GHz. Measurements were taken under the following conditions: operation setup, operation setup with damper circuit, gaps shorted by one plate (gap short@1). It was found that res-

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onance modes actually exist in the several hundred MHz region regardless of the conditions. We are constructing a circuit model that can reproduce high resonance frequencies by incorporating the components of a cavity, and are studying methods for analyzing and reducing high resonance frequencies.

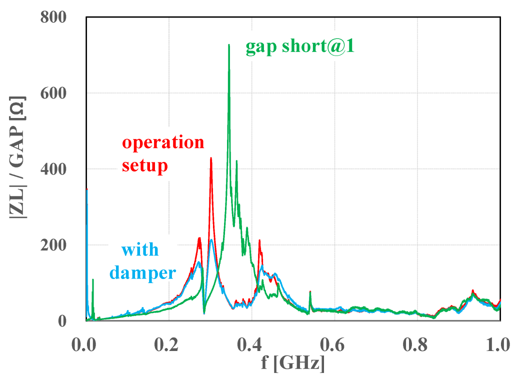

Figure 4: The impedance of a 4-gap cavity measured by the stretched wire method. Resonant modes exist in the region of several hundred MHz regardless of conditions.

Failure of Inverter Units

Figure 5 shows history of beam power and failures of inverter unit since 2015. Beam power below 60 kW indicate SX operation, and above 300 kW indicate FX operation. When the beam power exceeds 400 kW since 2016, the number of failures of inverter unit has increased, and in fact many inverter units have failed during FX operation. The inverter units of the APS are connected in parallel. Therefore, even if the inverter unit fails, the operation can be restarted after disconnecting the failed inverter unit. Since the current limit of the APS is lowered, the beam intensity is limited. Most of the failures were damage to the gate board and IGBT.

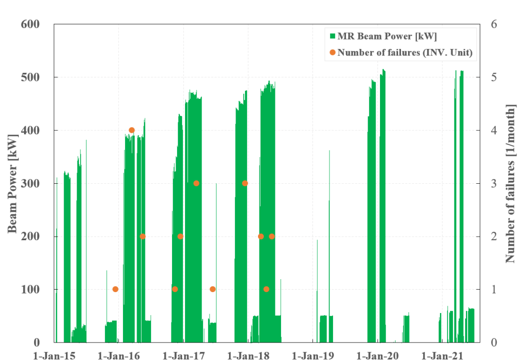

Figure 5: History of MR beam power and number of failures (inverter units) since 2015.

Figure 6 shows ferrite cores (KEMET ESD-SR-150) for noise suppression on the gate board used in the failed inverter unit. Cable ties and cables passing inside the ferrite core were discolored. Some inverter units that did not fail showed similar discoloration. Due to the temperature rise inside the

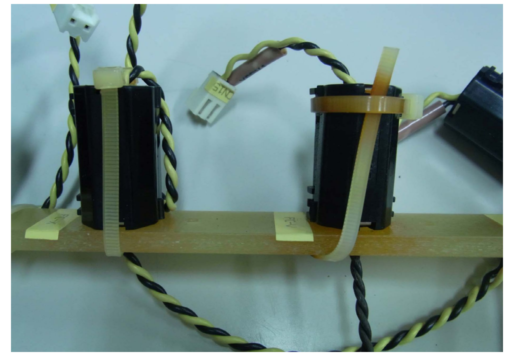

Figure 6: A noise filter in the failed inverter unit.

power supply building, the surface temperature of the ferrite element indicates 60 °C or higher. We replaced to the ferrite cores (TDK HF70RH26×29×13) having excellent inductive resistance and heat characteristic. In addition, the position of the cooling air outlet was changed so as to lower the temperature around the APS. Since these improvements, no failure of inverter units has occurred during user operation.

SUMMARY

J-PARC MR is implementing an upgrade plan for increasing beam power based on the high repetition scenario. In this plan, the accelerating time will be shortened from 1.4 s to 0.65 s or less, and the required accelerating voltage will be 500 kV or higher. In the required two sets of 2^{nd} harmonic RF systems, two 4-gap cavities are already installed in the beamline. At present, the first power supply is installed and ready for operation. The second power supply will be installed in 2023, and the 2^{nd} harmonic RF systems for the design value of 750 kW will be completed. Subsequently, two additional sets of high field gradient accelerating RF systems and upgrade to increase output current capacity of the APS by adding four inverter units are planned for 2023-2025.

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