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PRESENT STATUS AND FUTURE UPGRADES OF THE J-PARC RING RF SYSTEMS

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Abstract

J-PARC facility is the multipurpose research institutes. 10 years have passed since the user operation started. We have been considering the accelerator upgrades for the future and the target beam powers for 3 GeV rapid cycling synchrotron (RCS) and 30GeV Main ring (MR) are 1.5MW and 1.3MW, respectively. To achieve a 1.5MW of RCS output beam power, increasing the number of Linac proton particles is necessary. For accelerating such higher beam current, the ring rf systems in the RCS need to upgrade an accelerating voltage and to take into account for heavier beam loading compensation. In case of the MR, increasing the number of proton particles is not appropriate from the viewpoint of space charge effects. We choose to shorten the MR cycle time to increase an output beam power. The required accelerating voltage becomes almost double. All nine systems were replaced to realize the required voltages with the higher accelerating gradient RF systems using a newly developed magnetic alloy material. At present, the proton beam of 470 kW is being delivered to the T2K experiment with a cycle time of 2.48 s. Beam powers of MR will plan to aim first at 750 KW after replacing the magnet power supplies. But, to realize a 1.3 MW of the target beam power, the upgrade of RF power sources will be necessary. We report the present status of the ring RF systems and the upgrades for the future.

INTRODUCTION

The J-PARC facility is the multipurpose research institutes and consists of a 400 MeV Linac, a 3 GeV rapid cycling synchrotron (RCS) and a 30 GeV main synchrotron (MR). The designed output proton beam powers are 1 MW and 0.75 MW for the RCS and the MR, respectively. In the RCS, we achieved the output beam power of 1 MW in 2015 [1]. The 1 MW user operation for the Material and Life science Facility users will start after the neutron target for 1 MW high intensity beam becomes ready. For the future intensity upgrade in the RCS, we are planning to increase pulse width and peak current of the Linac beam. To accept such an intense number of protons, the longitudinal parameters and the concerned hardware are reconsidered. In the case of the MR, we are going to achieve the beam power upgrade by increasing a repetition of the MR cycle. At present, the period was changed up to 2.48 seconds from the original 3.64 seconds. The output beam power has reached 480 kW in the T2K user operation. In order to realize the designed beam power of 0.75 MW and more, we have been proceeding with replacements of main components in the MR. The new magnet power supplies for the BM's and QM's were designed with full energy recovery based on the capacitor banks, so that the induced power variation on the electrical grid could be sufficiently suppressed. The other component is the MR-RF systems. We developed new magnetic alloy material (FT-3L) to realize higher accelerating field gradient cavity. We designed 4- and 5-GAP cavities and replaced with all nine original 3-GAP cavities in 2016.

RING RF SYSTEMS

The RF cavities for the RCS and the MR are loaded with the magnetic alloy materials. The high accelerating field gradient of more then 20 kV/m is realized for the RF system of the medium energy proton synchrotron. The systems do not have a frequency tuning control, unlike a conventional ferrite loaded system. An impedance of the cavity covers an accelerating frequency range for each RCS and MR. The Q-values of the RF systems is optimized according to that frequency range. Combining with a full digital low level RF control, such passive cavity impedance can generate desirable multi-harmonic RF signals.

RCS RF Systems

The RCS is a triangle and has three straight areas. One of the areas is used to locate 12 RF cavity systems providing the 3 accelerating gaps. Ramping pattern of the main magnet is operated in sinusoidal with a 25 Hz repetition. Protons from the Linac are accelerated from 400 MeV to 3 GeV. The accelerating frequency changes 1.22 MHz to 1.67 MHz with an RF harmonic of 2. Controlling the bunching factor, which is defined by the ratio of an average current and a peak current of a circulating beam, is the most important longitudinal issue to alleviate the effects of the space charge force. Longitudinal manipulation during the injection and the beginning of acceleration periods are performed by applying a second RF potential, phase sweeping and momentum-offsetting methods. And, the multi-harmonic feedforward system has been designed to compensate the induced voltages by intense circulating proton beam [2]. Two Tetrodes (TH589/TH558) are used in a final stage amplifier for driving each cavity. The anode dc power supply is based on the IGBT (Insulated Gate Bipolar Transistor) -switching devices consisting of the 15-inverter output units connected in parallel. The maximum ratings are 13 kV and 92 A with a 60 % duty cycle.

RCS cavities are driven by multi-harmonic RF signals which correspond to accelerating RF signal (h = 2), longitudinal manipulation signal (h = 4) and the feedforward RF signals (h = 1, 2, 3, 4, 5, 6). The multi-harmonic operation is thanks to the wideband cavity impedance and the precise digital RF control. However, it cannot avoid that the current of each tetrode becomes unbalance in push-pull mode due to even harmonic component [3]. Moreover, the peak anode current came to the limit during the high intensity beam commissioning. Finally, we upgraded the output current capability by adding the output inverter units in 2015. We have successfully demonstrated the acceleration of 1 MW equivalent protons in the RCS.

Further Upgrade for the RCS RF Systems

The anode supplies were completed the modification of 19-inverter units. The current limit increases 30 % higher than the original one. The remaining issue is to solve unbalance of two-tetrode operation in the push-pull mode. It will become more serious during proton intensity increasing. A single-ended configuration is reconsidered instead of the push-pull one. The existing 12 RF cavities also need to be modified so that two-tetrode tubes are connected to the accelerating gap separately.

We designed the new re-entrant cavity cell loaded with the FT-3L cores [4]. The length of 4-cell system is compatible to the original 3-GAP cavity. The existing tube amplifier can drive the new cavity system by changing the connections of RF feeders [5]. The major RCS RF parameters are summarized in Table 1.

Table 1: Major RCS RF Parameters

Beam Power	**1MW**	**1.5MW**
Protons per pulse	8.33×10^{13}	1.25×10^{14}
Repetition rate	25Hz	25Hz
Accel. Time	20 ms	20 ms
V_{acc} (h=2) # of system	420 kV 12	440 kV 12
RF harmonics	2	2
Shunt impedance	400 Ω	450 Ω
Number of gaps	3	4
Resonant freq.	1.7 MHz	1.7 MHz
Q-value	2	6
Type of Tube Amplifier	Push-Pull	Single-ended
Type of cores	FT-3M	FT-3L
Size of cores(OD x ID x t; mm)	800 x 375 x 35	800 x 375 x 25
Number of cores	18	20

MR RF Systems

The main synchrotron (MR) accelerates the proton beam from 3 GeV to 30 GeV. The accelerating frequency changes 1.67 MHz ~ 1.72 MHz by 3 %. The optimum Q-value for the MR RF cavity is selected around 20 by applying the cut-core configuration [6]. The MR RF systems also do not have the tuning control. The MR has the 9 RF systems, and 7 systems are used for acceleration and 2 systems are used as the 2nd harmonic system.

In 2016, we have finished the replacement of all 9 RF cavities. The purpose of the cavity replacement was to achieve a required voltage for high repetitive operation. We developed a new magnetic alloy material (FT-3L) to realize higher accelerating field gradient cavity of over 30 kV/m and designed the 4- or 5-GAP cavities so as to increase the number of accelerating gaps per RF source as possible [4].

The MR circumference of the MR is 4.5 times longer than the RCS one. The RF harmonic is 9. The eight longitudinal buckets out of 9 are filled with the RCS bunches. The injection time during the four RCS transfers is 0.12 seconds and the acceleration time is 0.9 seconds including the two parabolic smooth-ramping times of 0.1 second. The fundamental (h = 9) accelerating voltages are 160 kV during the long injection period. Since the longitudinal bucket does not match to the RCS buckets, the 2nd harmonic (h = 18) voltages of 110 kV are added for diluting the longitudinal distribution to keep the circulating peak current low as much. Then, after 4 butches injection, the accelerating voltages are increased linearly to 310 kV with 0.1 seconds. Contrarily, the 2nd harmonic voltages are down to zero. The multi-harmonic feedforward systems of both the fundamental and 2nd harmonic systems are applied to cancel the beam induce voltages of the driving harmonic and two neighbor harmonics. At the present, the MR has been supplying 480 kW of proton beam to the T2K neutrino experiment with a cycle time of 2.48 seconds. This particle number corresponds to about 700 kW equivalent protons from the RCS. However, the longitudinal dipole oscillations have begun to be observed frequently around over 480 kW. These oscillations are based on the coupled bunch oscillation of the mode-8. The impedances of h = 8 seen by the beam seem to trigger the instabilities. We have initiated to develop the feedback control system for dumping the dipole oscillation, which is going to be implemented into the new digital control systems.

Beam Power Upgrade for the MR

The beam losses near the fast beam extraction area limit the circulating proton current and another concern is the peak current deficiency of the anode power supplies such things happened in the RCS RF systems. Figure 1 shows the plots of the peak anode currents versus a circulating proton number. The present anode power supply (15-unit version) limits 2×10^{14} ppp for the 5-GAP cavity and 2.8×10^{14} ppp for the 4-GAP cavity. Even if the longitudinal instabilities are managed, the full intensity from the RCS might be difficult to accelerate in the MR. To accelerate more proton beam and to reach the designed beam power of 750 kW, the following steps are being considered:

A) 2×10^{14} ppp accelerate with 1.28 seconds cycle
B) 3.3×10^{14} ppp accelerate with 1.16 seconds cycle

To realize the higher repetition cycle, we designed the new magnet power supply. Production of the new power supply has been started since 2015. Through the testing processes in practical user operation, all power supplies will be replaced by JFY2021. At the same time, the replacements for the fundamental RF system had been finished in 2016. We are now preparing the 2nd harmonic systems as the next. According to the earliest schedule, the MR will commence the 1.28 seconds operation in the end of JFY2021.

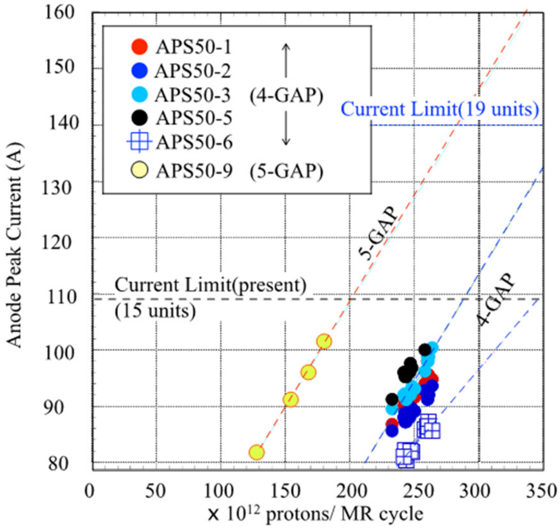

Figure 1: Variations of the Anode Peak Current of each MR system versus the circulating proton number.

The operation of 750 kW will be achieved by accelerating the 2 x 10^{14} protons per pulse with the repetition cycle of 1.28 seconds. These numbers are equivalent to 60 % of the full intensity beam in the RCS. The minimum required accelerating voltage is 510 kV. The synchronous phase becomes 30° degrees.

To accelerate the 3.3 x 10^{14} protons per pulse in the MR, the anode peak current of over 130 A is expected (see Fig.1). The anode power supplies of the MR RF systems are also necessary to upgrade their output current capability by adding the four additional inverter output units.

Table 2: Major MR RF Parameters

	750kW	**1.3MW**
Protons per pulse	2 x 10^{14}	3.3 x 10^{14}
Cycle time	1.28 s	1.16 s
Accel. time	0.65 s	0.58 s
V_{acc} (h=9)	510 kV	600 kV
# of system	9	11
V_{2nd} (h=18)	120 kV	120 kV
# of system	2	2
Synchronous phase (degree)	30	29
Harmonic #	9	9
Number of gaps	4	4
Resonant freq.	1.72 MHz	1.72 MHz
Q-value	21	21

The maximum repetition rate of the new magnet power supplies is 1.16 seconds according to the realistic numerical circuit simulation. The accelerating time becomes 0.58 seconds and the maximum dB/dt increases about 12 % in this case. To cover the required accelerating voltage of 600 kV, the two additional high field gradient accelerating systems are proposed. The major RF parameters based on a particle tracking are listed in Table 2.

SUMMARY

The J-PARC is the multi-purpose proton accelerator facility and the accelerator consists of the Linac, the 3 GeV RCS and the 30 GeV MR. The RCS delivers the 3 GeV intense proton beam to the MLF and to the MR for further acceleration. In the MR, the 30 GeV proton beams are delivered to the neutrino facility with a fast extraction mode and to the hadron facility with a slow extraction mode. The output beam power of the RCS has been reached to the designed beam power of 1 MW. For the stable 1 MW operation, the anode power supplies of the RCS RF systems were modified to avail the higher output peak current. However, imbalance behaviour of the vacuum tubes used in a push-pull final stage amplifier become serious impediments for further intensity upgrade. We have been designing the new FT-3L loaded cavity with the four accelerating gaps and investigate introducing of the single-ended driving method, in order to overcome this effect. In the case of the MR, the beam power has been reached to 495 kW with the fast extraction mode. To realize the designed beam power of 750 kW, manufacturing the magnet power supplies and two sets of the 2nd harmonic RF system are going on. In 2022, we are planning to start the beam commissioning with the high repetition cycle. For further beam power operation, upgrading the anode supplies of the MR RF systems is indispensable and constructing the two additional accelerating RF systems are necessary to operate the required accelerating voltages. Finally, we are aiming the target beam power of 1.3 MW in the MR.

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