STATUS OF THE J-PARC MA LOADED RF SYSTEMS

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Abstract

Japan proton accelerator research complex operates two cascaded synchrotrons, 3GeV RCS, and 50GeV MR. The high electric field gradient magnetic alloy (MA) loaded cavities are used in both synchrotrons. These RF systems have no tuning control loop and the direct digital synthesis based fully digital low level RF guarantees the stable and reproducible proton acceleration. The feedforward systems using the circulating beam current signals work efficiently to compensate the heavy beam induced voltage. In the RCS, 11 RF systems are operating in a dual harmonic mode since December 2008. The longitudinal RF control based on the particle tracking performed effectively and the equivalent beam power of 530 kW was successfully demonstrated. The 260 kW operation for the neutron users started in October 2012. In the MR, the 9th RF system was newly installed and became available as a 2nd harmonic RF system in November 2012. A 30 GeV proton of 200 kW beam power has been delivered to the T2K neutrino beam experiment with 2.48 sec repetition cycle. This paper summarizes the operation details and the status and features of the J-PARC RF systems.

INTRODUCTION

The J-PARC facility is a high intensity proton accelerator complex, consisting of the 181 MeV Linac, the 3 GeV Rapid Cycling synchrotron (RCS) and the Main synchrotron (MR). Stable high intensity proton beams are delivered: 300 kW for the neutron users of the MLF and 30 GeV 230 kW beam for the neutrino T2K experiment and 15 kW beam for the hadron experimental groups. The magnetic alloy loaded accelerating systems are utilized for stable and reproducible acceleration in the synchrotrons. The MA loaded system has wideband impedance. Then, the frequency tuning is not necessary. The magnetic alloy material is very stable against a high operating magnetic field because of its high saturation magnetic flux density and high Curie's temperature. The MA system acts as a passive load. The digital low level RF system is the best combination with the MA loaded RF systems. In the RCS, 11 RF systems are operated in a dual harmonic mode, which can be used for acceleration and longitudinal manipulation of the high intensity beam in the available space. Beam loading compensation is an important issue. The feedforward method using the wall current RF beam signals has been established. In the MR, 9 RF systems are operational in total, including one 2nd harmonic RF system. In this paper, we report more details about the MR RF system and the commissioning status since last year.

BEAM COMISSIONING

The J-PARC beam commissioning has been started with the181 MeV Linac energy. In this case, the output beam power in the RCS is limited to 60% by the space charge tune shift. Until now, a 550 kW equivalent beam was extracted from the RCS as a high intensity trial and the 300 kW beam is steadily delivered to the MLF and the MR. The nominal machine cycle of the MR is 6.0 seconds for the Hadron experiment (SX: slow beam extraction by using a third-integer resonance) and 2.48 seconds for the Neutrino experiment (FX: fast beam extraction by using the fast kicker magnets). The MR cycle for T2K experiments has been set 30 % shorter than the original cycle of 3.64 seconds to obtain more output beam power. The number of accelerating particles per pulse exceeded 1.2 × 10^{14} (120 Tera) protons at the user run. The output beam power corresponds to > 230 kW. But, this number is at limit with the present H- ion source.

Table 1: Major Parameters

	3GeV RCS	MR
Energy (GeV)	0.181 – 3	3 – 30
γ_t	9.14	j36.1 *1
Circumference (m)	348.333	1567.9
Intensity (ppp) *2	$3.\times10^{13}$ (8.3×10^{13})	1.2×10^{14} (3.3×10^{14})
Cycle/period	25Hz	2.48 s (FX) 6.00 s (SX)
Acc. Voltage (kV) *3	400	280
RF harmonics	2	9
No. of RF stations	11 (12)	8 + 1*4
No. of Acc. Gaps	3	3
Voltage per cavity*2	36 kV	35 kV
Cavity length (m)	1.996	1.846
Q-value	2	22
Cavity Impedance*5	890 Ω	1100 Ω

* Numbers in () are the design values. *1: imaginary energy, *2: Nominal values during user run, *3: voltages at peak, *4: 2nd harmonic cavity, *5: Impedance per gap

High Intensity Operations

For high intensity operations, the incoherent tune shift must be suppressed by increasing the bunching factor. The 2nd harmonic systems are effective for keeping the bunching factor high. In case of the RCS injection, the bunching factor of 0.4 is required. The RCS RF cavities have a Q-value of 2. The impedance covers the 2nd harmonic frequency. The LLRF generates both the h = 2 and h = 4 amplitude patterns and the combined RF signals are fed into each cavity. In that way, the 2nd harmonic voltages are applied during the longitudinal painting with momentum offset and 2nd harmonic phase sweep at time and after the multi-turn injection [1]. Figure 1 shows the recent RF voltage amplitude patterns for the RCS RF systems. The second harmonic voltage is applied up to 5 msec from the injection, instead of the previous value of 3 msec, according to the recent particle tracking suggestion.

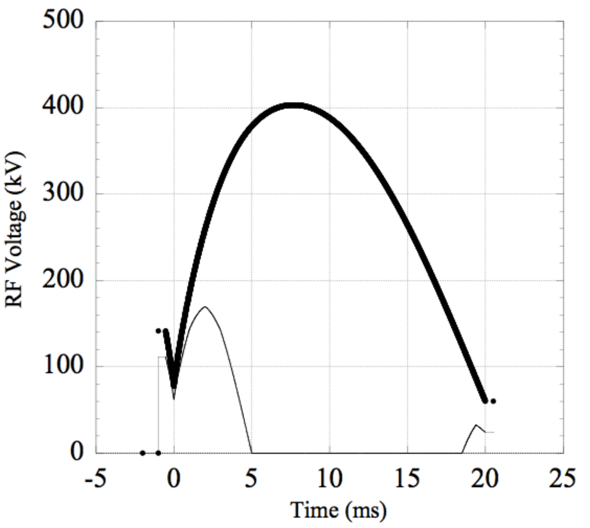

Figure 1: Typical voltage patterns with 2nd harmonic rf in the RCS. The 2nd harmonic amplitude has a maximum value at 2 ms, 80% of fundamental rf amplitude. The 2nd harmonic amplitude at the end of acceleration is not applied during the normal user operations.

Longitudinal Injection Matching

The longitudinal matching is one of the issues during the high intense bunched beam transfer between the RCS and the MR. Eight bunches from the RCS fill eight of nine empty MR buckets by 4 RCS transfers. The nominal values of the bunching factor and the longitudinal emittance of the RCS beam are 0.15 and 5 eVs, respectively. Those longitudinal parameters must be enlarged in future. Controlled longitudinal emittance blow-up becomes important to avoid the beam losses due to the space charge effects. Applying the high frequency cavities (HFC) in both the RCS and the MR has been investigated by the particle tracking code [2], [3]. The HFC system in the MR could be particularly effective for improving the spill structure during the slow beam extraction. We started a design work.

With regard to the longitudinal matching, we have studied with a 2nd harmonic RF system while carefully comparing with a particle tracking. Figure 2 shows the consistent results from the tracking study. We have obtained one of the methods to keep the bunching factor constant during the MR injection.

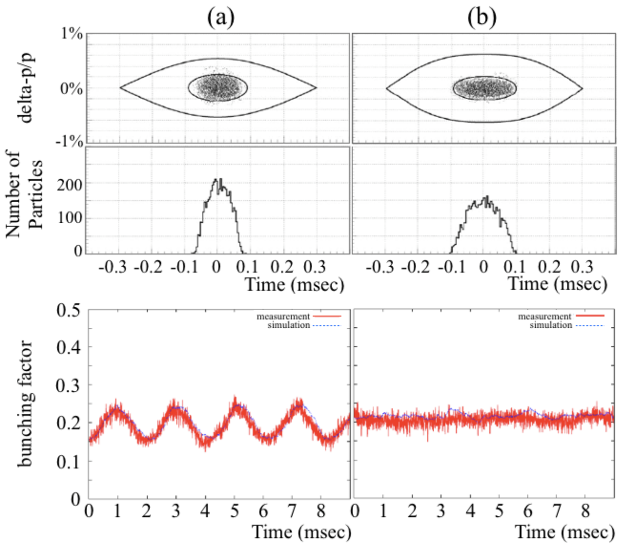

Figure 2: The simulated longitudinal distributions at the MR injection (top) and the time variations of the bunching factor during the injection period (bottom); (a) MR fundamental RF is 90 kV, (b) MR fundamental RF is 120 kV and 2nd RF is 36 kV. Also, 2nd RF is applied at the end of the RCS extraction (see Fig.1).

Beam Loading Compensation for the MR

The MR RF systems consist of 8 accelerating (fundamental h=9) systems and one 2nd RF system. The impedance of each cavity is narrower (Q ~ 22) than that of the RCS cavity. The systems are driven by a single harmonic RF signal of h = 9 or h=18. However, the wake voltage induced in the fundamental RF cavity has not only the accelerating harmonic (h = 9) but also the neighbor harmonics (h = 8, 10) (Fig.3). In case of the 2nd RF system, the harmonics become h = 17, 18, 19. So, the multi-harmonic beam loading compensation is indispensable to cancel the induced wake voltage in the cavity. We have developed the feedforward system similar to the method in the RCS [4].

The digital I/Q signal processing in the feedforward system analyzes each of the three harmonic components of the circulating beam by using a wall current beam monitor. The compensation gain and phase (FF output signal in Fig.3) of each harmonic are calculated according to the transfer function of each RF system.

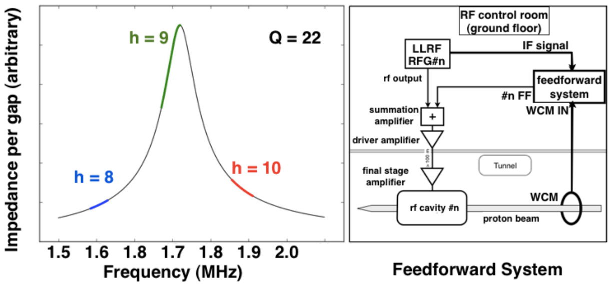

Figure 3: The frequency response (schematic) of the accelerating gap (when Q = 22) and the positions of the harmonics seen by the beam and the schematic view of the feedforward system

Since the transfer function of the final stage amplifier slightly changes according to the output power, the commissioning of the feedforward system has been carried out with a high intensity proton beam, for instance, 1×10^{14} ppp in case of the MR. The impedance seen by the beam has been greatly reduced. The longitudinal oscillations due to the wake voltage are successfully suppressed by the multi-harmonic feedforward [5].

IMPEDANCE OF MR CAVITY

The MR cavity uses the MA cut-cores to adjust the desired Q value of 22. Several processes, “water jet”, “epoxy resin impregnation”, “diamond polish” and so on, have been combined to make a cut core. The MR beam commissioning started on May 2008. However, the MA cavities have suffered from impedance reductions due to corrosion under the condition of pure cooling water with extremely low dissolved oxygen since September 2009 [6]. To solve the impedance reductions, we developed a silica coating on the cutting section and covered the gap spaces between two halves of the cut core with FRP plates and RTV rubber to prevent cooling water from penetrating into the cut surface. Also we separated the RF cooling system from the magnet cooling system in 2011. Replacement of the cut-cores completed on September 2012. The impedance of each cavity looks stable and no impedance reduction has been observed since the core replacement (Fig.4).

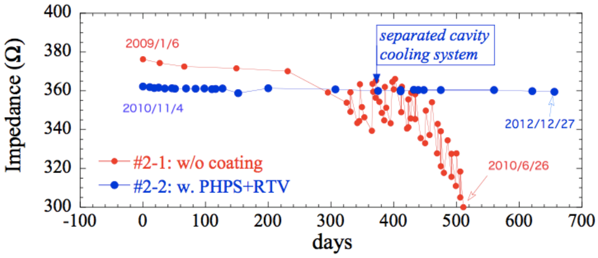

Figure 4: Time variation of the cavity impedance at station#2. “Red” shows the impedance of the original cavity and “Blue” shows the impedance of the cavity using the cut-cores protected from water penetration.

OUTLOOK

In the J-PARC Linac, the 400 MeV energy upgrade is carried out in 2013 and the ion source upgrade will be in 2014. In the RCS, the injection systems are replaced for 400 MeV-injection and re-alignment work for all lattice magnets is scheduled, and a new 12th RCS cavity is installed in summer 2013 for providing further high intensity operation. In the MR, the high repetition cycle scheme towards higher repetition cycle operation is currently in progress to realize the design beam power of 0.75 MW with the proton energy of 30 GeV. 60 % or more of the accelerating voltage is required. New type (FT3L) of cores for the accelerator application were successfully manufactured at the J-PARC site in 2011 [7]. By using these cores, the existing 9 MR 3-GAP cavities are going to be replaced with 4-GAP or 5-GAP cavities by 2016. Then, the numbers of acceleration gaps become 53. The power loss of the FT3L core is less than half of the ordinary MA core (FT3M). By using the cavities loaded with FT3L cores, we can accomplish a required RF voltage on the limited conditions of the RF power supply and the installation space. Mass productions of the cores and the cavities have been started in JFY2013.

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