# RECENT STATUS AND FUTURE PLAN OF J-PARC MA LOADED RF SYSTEMS

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*Abstract*

Japan proton accelerator complex (J-PARC) includes 3GeV rapid cycling synchrotron (RCS) and 50GeV main ring synchrotron (MR). Both synchrotrons use the high field gradient magnetic alloy (MA) loaded cavities. In RCS, 11 RF systems have been fully operational since December 2008. The RCS RF systems are performed in dual-harmonic mode. Beam acceleration and the bunch shape manipulation are efficiently taking place. 120kW extracted beam power for neutron user operation at the Material and Life science facilities was started in November 2009. In MR synchrotron, the 5th RF system was installed in August 2009, and 5 RF systems are now in operation. Beam commissioning for delivering protons to the hadron facility and neutrino beam experimental facility are under way. The beam delivery to the neutrino user experiment started in January 2010. Proton beam operation with more than 100kW is required. The approaches to realize high intensity operation and the MR upgrade plan will be presented.

## INTRODUCTION

J-PARC is a high intensity proton accelerator complex, it consists of 181MeV linac, 3GeV rapid cycling synchrotron (RCS) and 50GeV main synchrotron (MR). Since the beam commissioning of J-PARC starts, the beam intensities or beam powers are increasing steadily. And, 300kW proton beam has been successfully extracted from the RCS to the MLF (Materials and Life Science Facility) neutron facility. In MR, a 30GeV proton beam is delivered to both the hadron experimental facility and the neutrino target for T2K experiment. Slow beam extraction with 3$^{rd}$ resonance scheme is the key in J-PARC MR Hadron user experiments. To reduce the effect of the magnetic field ripples of the quadrupole power supplies becomes the most important issue to improve the spill structure of the slowly extracted proton beam. Beam tuning and delivery are performed with several kW proton beam. On the other hand, 100kW proton beam acceleration has been demonstrated in MR and 70kW beam operation has been started for T2K neutrino experiments.

## RF SYSTEMS

Magnetic alloy loaded accelerating cavities are used in both the RCS and MR synchrotrons [1]. Magnetic alloy has a high $\mu Qf$-product, which can realize the high shunt impedance ($R_p$) of cavity. Because of high saturation flux density and high curie's temperature, MA loaded system can achieve more than twice higher accelerating field gradient (> 20kV/m) than the ferrite loaded RF system. The RCS is a compact rapid cycling (25Hz) synchrotron. The RF cavity was designed for a wide frequency bandwidth to cover both fundamental (0.938MHz ~ 1.67MHz, h=2) and 2$^{nd}$ harmonic. Therefore, the RCS cavity can be used for beam acceleration and bunch shape manipulation by adding the superimposed RF voltages. The optimum Q-value is selected Q=2 [2]. Because of large R/Q, multi-harmonic feedforward and/or feedback are employed to compensate the voltage distortions [3].

The frequency change is only 3% during the acceleration in case of MR. To avoid periodic transient beam loading, the Q-value is chosen 20-30 by using the cut-core configuration [4].

Magnetic alloy material of the RF accelerating cavity is behaving as a passive load. Therefore, the tuning control loop is not necessary and not provided. Combining a digital LLRF based on DDS with MA loaded system, precise and accurate longitudinal control can be realized. The J-PARC RF system is the first high field gradient accelerating system, which is loaded by the magnetic alloy materials, for the high current proton synchrotron.

## RCS BEAM COMMISIONING

To increase the bunching factor (defined by Bf = average current/peak current), the momentum offset injection scheme and bunch shaping using 2$^{nd}$ harmonic voltage are applied during the injection to the early accelerating period [5]. Large amplitude of 2$^{nd}$ harmonic RF voltage effectively allows the hollow bunches in the longitudinal phase plane. Consequently, the required bunching factor of 0.45 has been achieved. Longitudinal manipulations are parameterized by particle tracking code. Longitudinal particle motions are consistent with the tracking results [6].

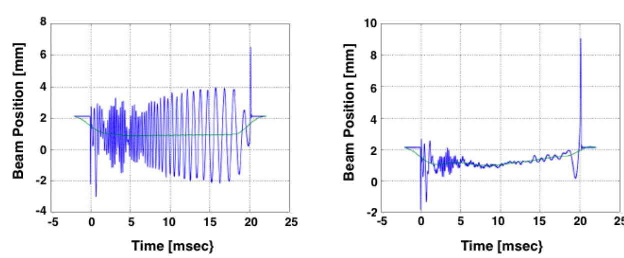


Figure 1: Beam phase plot during the whole acceleration. (Left): Phase Feedback OFF (Right): Phase feedback ON

Since the beam commissioning started in RCS, the beam power had been comparatively going well. This is due to stability of the linac beam, the bending field, and the accurate timing system. Practically, Δr and Δϕ beam feedbacks were not necessary for below 100kW proton beam operation.

The phase feedback works properly and damps the dipole oscillation (Figure 1). The beam phase at extraction depends on the circulating beam intensity. The feedback gain is patterned to minimize jitter of the extraction beam (Figure 2). The jitter width of the extracted beam from the RCS is 1.7ns.

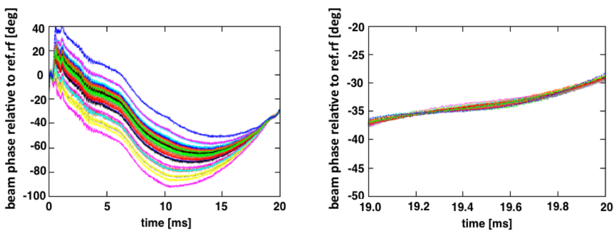


Figure 2: Beam phase plot during 1-hour 300kW operation (190 shots plotted). (Right): magnified (19 – 20ms).

Feedforward control is one of key scheme for high intensity operation. Multi harmonic beam induced voltages need to be suppressed. The feedforward system processes the wall current monitor signal and generates the harmonic compensation signals (h=2,4,6) so that the beam induced voltages are cancelled [3].

The 11 RF systems are operational in the RCS. The transfer function of each system has slightly different behavior because of an individual frequency characteristic. The gain and phase for each harmonic component on each RF system must be optimized to cancel the induced voltage by the beam. The gain/phase optimization is under way.

Up to 300kW, the beam acceleration is stable even without the beam loading compensation.

## MR BEAM COMMISIONING

Four-batch injection scheme fills 8 buckets in the MR synchrotron. Since the harmonic number of the MR is 9, one empty bucket is reserved for the rising time of the extraction kicker. The beam commissioning has been started with 6 bunches and the top energy of 30GeV. In January 27, 2009, 30GeV protons were successfully extracted to Hadron Experimental Hall with 3$^{rd}$ resonance extraction scheme, and in April 23, 2009, extracted, with the fast extraction kicker system, to the neutrino beam line for the T2K experiment, with 4 RF stations in MR. In August 2009, the 5$^{th}$ RF system was installed. The cycle and accelerating period were changed 3.52 sec and 1.9 sec, respectively. The real beam tuning to the user operation began.

The bunching factor of the MR injection beam is required to be more than 0.15 for 100kW operation. In case of single harmonic RF, the required RF voltage at injection is around 80kV to minimize quadruple oscillations. Once acceleration starts, however, the RF voltage must be higher to keep the sufficient bucket height, especially during the parabolic ramping region (Figure 3).

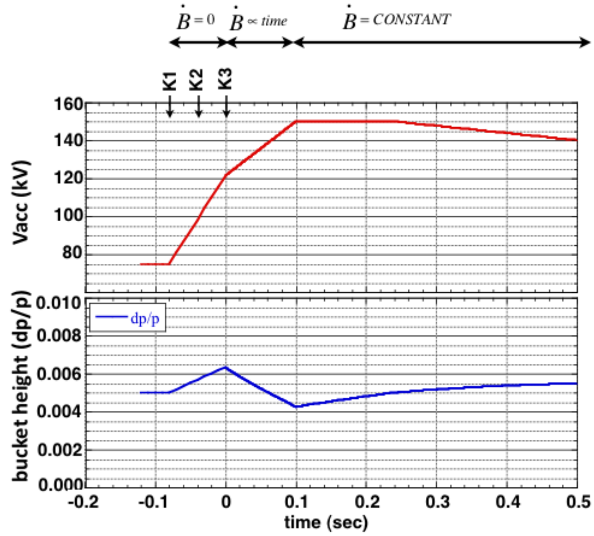


Figure 3: Typical RF voltage pattern and the bucket height (dp/p) near beginning of acceleration. Beam injections are at K1, K2, K3, and acceleration starts at t=0. Bending field is parabolically ramped between t = 0 ~ 0.1 sec and B-dot is constant t > 0.1 in Figure.

A high intensity trial in the MR has been successfully carrying out. With systematic tune surveys and transverse orbit corrections, 100kW proton beam were successfully accelerated and extracted without significant beam loss. And, 70kW user operation has started for the T2K neutrino experiments.

## CAVITY IMPEDANCE

In December 2008, the impedance reduction was found at one of 11 RCS cavities [7]. Afterwards, the similar changes happened three times. In January 2009, the summer shutdown 2009 and March 2010, the cavies were opened to replace the cores. And, we found that this impedance reduction was due to the core buckling. The crack was caused by such deformation in the core.

The 18 toroidal cores, so-called un-cut core, are used in the RCS cavity. In case of un-cut cores, the RF magnetic flux density $B_{rf}$ is proportional to 1/r, where r is a radius. The power dissipation is higher at the inside of the core. And also, the cores are manufactured by impregnating a low-viscous epoxy resin inside and finished by covering an epoxy coating with an 180$\mu$m glass cloth for preventing from corrosion. In the mean time, we have checked 90 cores of 5 cavities. 25 cores were found to show buckling, which the low-viscous epoxy resin was used in the manufacturing process. The relation between the low-viscous epoxy resin and buckling is clear. 180$\mu$m glass-cloth is not flexible and must be easier to peel off at the inner edge of the core. A local deformation by compressive stress caused by thermosetting process or thermal expansion is connected with the buckling. Compression stress is getting higher at the inside of cores during operation. To solve the buckling problem, the manufacturing process was improved [8]. To evaluate the cores in various manufacturing process, the following steps of examinations were performed,

Step 1: 125°C -30hr heat run with oven
Step 2: 125°C -20hr heat run with RF power
Step 3: 1000-hr RF high-power run at the test bench.

Finally, the process, which was passed all the examinations, was determined. Production of the cores is proceeding, and replacement with such cores is scheduled in summer 2010. To maintain the quality of cavity, a regular impedance measurement by a network analyzer and the online monitoring of cavity temperature and conductivity of cavity cooling water are continued.

Cut cores are used in the MR cavities, which realizes the high Q-value of 26. Power dissipation is uniform and the cores are thermally more elastic than the cores in RCS. However, as shown in Figure 4, all cavity impedances, including the 5th cavity newly installed, showed the tendency to drop the impedance since September 2009. Moreover, the impedance drop of cavity #1 became larger than the others in December 2009. 6 cores. The cavity #1 needed to be replaced in January 2010.

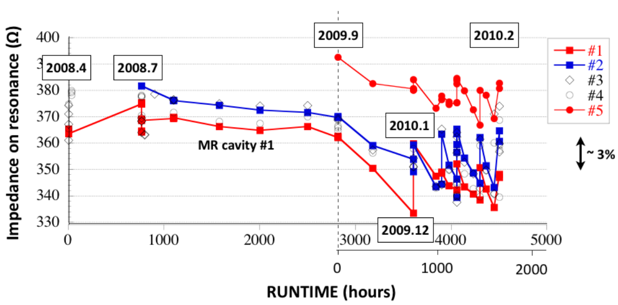


Figure 4: Trend graph of MR cavity impedance. All impedance measurements show the tendency to decrease since 2009.9

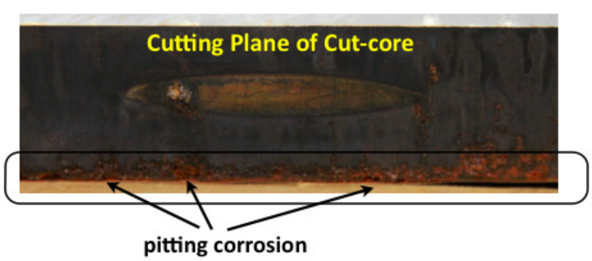


Figure 5: Pitting corrosion on the surface of the cut-core.

Until now, we have learned about the impedance drop of the MR cavity that (1) the cutting planes of core are damaged due to severe pitting corrosion (Figure 5), (2) the impedance recovers when the cores are exposed to the air (oxygen), (3) electric field, flow direction and Cu substance in cooling water seem to correlate with corrosions and (4) the core impedance can be recovered by re-polishing the surface.

Although the impedance recovers by exposing the cores to the air, its recovered value gradually is going down. In the present, 2 cavities have been operated with lower output power. To maintain the user's operations, the damaged cavity will be replaced and an additional filter in the cooling system will be added in June 2010. Moreover, 2 other cavities, which showed an impedance drop, will be replaced in the summer shutdown 2010.

Coating of the cutting plane is under development. Inorganic silica coating is the most promising method to prevent from corrosion and preliminary examinations such as 48 hours salt spray test and 300 hours high power test have been finished. In the long term, the RF cavity water-cooling system must be separated from other cooling systems, like magnet.

## POWER UPGRADE PLAN

Linac energy upgrade from 181MeV to 400MeV is planned in FY2012. In RCS, installation of 12th RF cavity is scheduled as well as the upgrade of injection system for 400MeV beam. To realize full beam power of 0.75MW in MR, several upgrade plans are considered as well.

(FY2010) Installing the first 2nd harmonic cavity. Replace the extraction kicker magnets for 8-bunch operation.

(FY2011) Install 6th RF cavity and the second 2nd harmonic cavity. Change the MR cycle to ~2.5sec.

(FY2012) Install the third 2nd harmonic cavity and a fixed frequency higher harmonic cavity [9] and shorten the MR cycle from 2.47s to 2.23s.

In this scenario, the maximum dB/dt is almost equivalent to the original designed value. For further upgrade and higher field gradient RF cavities, the development of new magnetic alloy material is now in progress [9].

## REFERENCES

[1] "Accelerator Technical Design Report for High Intensity Proton Accelerator Facility Project, J-PARC", JAERI-Tech 2003-044
[2] M. Yoshii et.al, "Present Status of J-PARC Ring RF System", PAC07 Albuquerque, NM, USA
[3] F. Tamura et.al, "Development of the feedforward system for beam loading compensation in the J-PARC RCS", EPAC06, Edinburgh, Scotland
[4] C. Ohmori et.al, "New cutting scheme of magnetic alloy cores for J-PARC synchrotrons", EPAC2006, Edinburgh, Scotland
[5] M.Yamamoto et.al, "Acceleration Voltage Pattern For J-PARC RCS", EPAC08, Genoa, ITALY
[6] M. Yamamoto et.al, "Longitudinal particle simulation for J-PARC", PAC09 Vancouver, CANADA
[7] M. Yoshii et.al, "Proton beam acceleration with MA loaded RF systems in J-PARC RCS and MR synchrotron", PAC09 Vancouver CANADA
[8] M. Nomura et.al, "Condition of MA cores in the RF cavities of J-PARC synchrotrons after several years of operation", in this conference
[9] C. Ohmori et.al, "Development of Magnetic Alloy Cores with Higher Impedance for J-PARC Upgrade", in this conference