ACCELERATION OF HIGH INTENSITY PROTON BEAMS IN THE J-PARC SYNCHROTRONS

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Abstract

The J-PARC accelerator complex consists of the linac, the 3 GeV rapid cycling synchrotron (RCS) and the 50 GeV main synchrotron (MR). These synchrotrons are the first MW-class proton accelerators, which employ the high electric field gradient magnetic alloy (MA) loaded RF cavities. The beam commissioning was started in October 2007 for RCS and in May 2008 for MR. High intensity beam operation studies and user runs have been performed, while carefully controlling and minimizing the beam loss. The cycle-to-cycle beam operation is reproducible and quite stable, because of the stable linac beam energy and the reproducible bending field in both synchrotrons. The MA loaded RF systems and the full digital LLRF also guarantee the stable longitudinal particle motion and precise beam transfer synchronization from RCS to the MLF user facility as well as to the MR. A high intensity proton beam of 2.5×10^{13} ppp is accelerated in RCS. And in MR, a beam intensity up to $\sim10^{14}$ ppp was obtained. We summarize the RF systems and the longitudinal parameters in both rings.

INTRODUCTION

Since the beam commissioning has been started, the intensity has been increasing steadily. In the RCS, 200 kW user operation has been started for the MLF since November 2010. And also, the high intensity beam acceleration was successfully demonstrated in a single shot operation with 400 kW equivalent intensity beam. On the other hand, in the MR, the high intensity beam delivery to the neutrino beam line was 60 kW in April 2010, but it became 135 kW in November 2010 and reached 145 kW in March 2011.

The feedforward beam loading compensation is a key system for cancelling a wake voltage at the MA loaded cavity. The commissioning of the feedforward system was started with using a 300 kW equivalent beam and completed to all 11 RCS RF systems. The feedforward has been used in the normal beam operation since October 2010.

In the MR, the 6th cavity was installed as a 2nd harmonic system in August 2010. We have started the beam study using 2nd harmonic RF. Furthermore, two RF systems are going to be installed in October 2011. Actual 2nd harmonic beam study will start in the end of FY2011.

In January 2009, the significant impedance drop was observed at one of the cavities in the RCS. Later, it became clear that the deformation of the several cores due to buckling causes the impedance reduction. We have improved the coating process. At present, a similar impedance drop was observed 4 times. We have replaced the damaged cores and the cores, which are likely to deform, during two summer shutdowns. The plan for the core replacement is scheduled. Impedance decrease in the MR is different from that of RCS. Since the cut core is used in the MR cavity, the possibility of buckling is low. However, because the cavities are supplied by the same cooling water as the MR-magnets, it became clear that copper ions are involved in the corrosion process.

CAVITY IMPEDANCE

The magnetic alloy cores used in the J-PARC are made of winding a thin amorphous ribbon. Then the core is especially annealed by heating above the recrystallization temperature. The quality factor is ~0.6, a lossy material. However, the μQf-product, which is proportional to the shunt impedance, is high, > 3×10^9 (Hz). The cavity impedance can become high enough with those cores. And also, the μ and Q properties of the MA material are stable under varying RF magnetic field density (Brf) and temperature. Therefore, the cavity impedance can be regarded as a passive load. No tuning feedback loop is necessary. By using a precise digital RF signal based on a direct digital synthesis (DDS), the RF system becomes stable and reproducible.

The RCS RF cavity is a broadband system, which covers the fundamental and the 2nd harmonic frequency band. The system can operate the 2nd harmonic RF system for bunch shape manipulation as well as the fundamental RF system for acceleration. It efficiently uses the long straight space along the ring. The Q-value of the cavity is optimized to be Q = 2 by adding an external low-loss inductor and tuned to 1.7 MHz by selecting an appropriate gap capacitor [1]. 18 un-cut cores are used per cavity. In case of MR, the MR cavity uses 18 cut cores differently from the RCS. The distance between two halves is set to be 10mm to realize $Q \sim 25$ at the fundamental ($h=9$) accelerating frequency. The MA cores in the cavities are cooled by deoxidized pure water.

Coating Processes

To prevent from corrosion, the magnetic alloy cores are manufactured by impregnating with low-viscous epoxy resin inside and finished by covering with an epoxy resin combined with a glass cloth. Impregnating low-viscous epoxy resin was the process following the cut-core manufacture to keep up the core strength. In December 2008, the impedance reduction was found at one of the RCS cavities. At present, a similar impedance drop has happened 4 times. We found that this impedance reduction was due to the core buckling. 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. Compression stress is getting higher at the inside of cores during operation. To solve the buckling problem, impregnating low-viscous epoxy resin was skipped from the manufacturing process [2] and the coating process was improved.

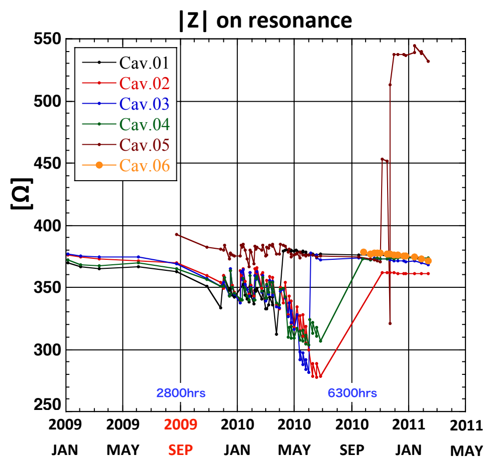

Figure 1: Impedance measurements of the MR RF cavities: Cav#5 started operation in 2009.9 and Cav.#6 in 2010.11, Cav#5 was operated with *h=18* or other different mode after 2010.10

Cut Core Production

A water jet is used to make a cut core. Since the cut surface after the water jet is not smooth enough, after finishing the low viscous epoxy resin impregnation, the diamond polish process is performed to keep electrical isolation on section. In May 2008, we have started the MR beam commissioning with four RF systems. And one year later, the system became the five RF systems.

The decrease in impedance was observed for the first time during slow extraction operation in September 2009. All impedances showed the tendency to decrease (Figure 1). Concentration of dissolved oxygen in pure cooling water is several tenth of ppb. We could not find any reason for severe corrosion. To solve the impedance reduction due to corrosion, a silica coating on the cutting section has been developed. And also, to prevent from permeation of reactive substances, the air gap spaces between two halves of the cut core are covered with a FRP plate and RTV rubber (Figure 2). Later, it became clear that the copper substance inside the cooling water accelerates corrosion, which causes severe corrosion on the cut surfaces [3]. In FY2011, the decision was made to separate the RF cooling system from the magnet cooling system. The construction work has been started in this summer.

Most of the cut-cores were replaced so far. Because there was little activation of some cores, only non-activated cores have been polished and re-used.

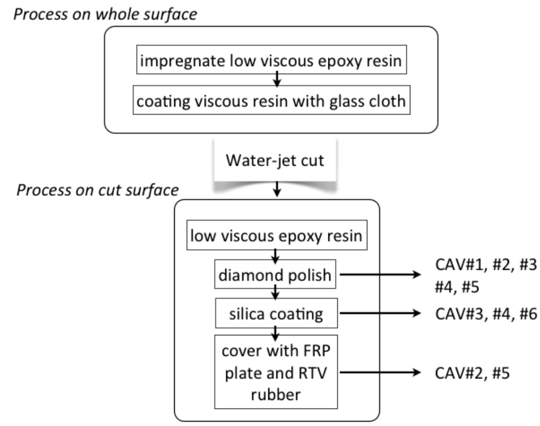

Figure 2: Cut Core Production Process: Five cavities (#1~#5) used the diamond polished cut-cores. Later, The cores of three cavities (#3, #4, #6) were replaced with the silica-coated cut-cores. Moreover, the cores of two cavities (#2, #5) were the more robust (using FRP plated and RTV rubber shield type).

HIGH INTESITY PROTON BEAM ACCELERATION

The RCS is designed to accelerate a high intensity proton beam from 181 MeV to 3 GeV in 20 ms. To suppress the space charge effects, the bunching factor must maintain a high value of more than 0.4 at the start of acceleration. The longitudinal painting with 2nd harmonics and with phase and momentum manipulations is the key in RCS and successfully working.

Feedforward Beam Loading Compensation

In a dual harmonic operation, each RCS cavity is driven by a superposition of the RF signals (*h=2* and *h=4*). Because the wideband RCS cavity has a large *R/Q* value, the beam-induced voltage is high, and it has a harmonic component. Therefore, a multi-harmonic RF feedforward system was developed to compensate an induced voltage [4]. The wake voltages at the accelerating gap is $V_w = I_{beam} \times Z_{beam}$, where V_w is a beam induced voltage, I_{beam} is a beam current and Z_{beam} is a cavity impedance seen by the beam. The feedforward system consists of the wall current monitor (WCM) and the feedforward module. The feedforward module analyses the beam current signal by an IQ modulation method and generates ($- i_{beam}$) so that the product of $G \times i_{beam}$ is equal to I_{beam}, where G is a transfer function of an amplifier chain. The transfer function G has frequency and amplitude dependencies. The feedforward module generates the gain and phase parameters for each RF frequency and for each harmonics. In RCS, the most major three harmonics, *h=2,4,6* are taken into account. And, we have established the commissioning methodology of the multi-harmonic RF feedforward. The commissioning has been performed with the 300 kW equivalent beams and for all 11 RCS cavities the parameter adjustments were successfully done. The impedance suppression seen by the beam achieved 30 dB at maximum. The feedforward has been successfully used in the normal beam operation since October 2010.

Bunch Shape Manipulation for MR Injection

The bunching factor of injected beam into the MR can be improved by introducing a 2nd harmonic voltage near the end of the RCS extraction. We have observed the bunch shape at the MR injection, when the 2nd harmonic voltages were applied in the RCS at extraction and the MR injection (Figure 3). Because of slow synchrotron frequency at the end of RCS acceleration, the bunch shape dose not match with an RF bucket. Therefore, the MR injection voltage is low to satisfy the matching condition. We confirmed that the 2nd harmonic systems worked properly and the bunching factor was improved by ~70 % in the beam study. However, the difference between the MR injection voltage and the accelerating voltage is large, the beam loss at the beginning of acceleration becomes an issue. The more precise particle tracking is under way.

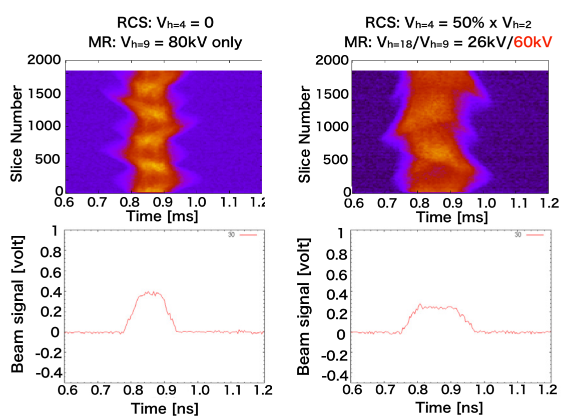

Figure 3: Mountain view and bunch shape at MR Inj. (Right): Injection without 2nd harmonic voltages in both RCS and MR. (Left): 2nd harmonic operations at RCS extraction and MR injection.

In FY2010, the first 2nd harmonic system was installed in the MR, and two more systems are ready in this summer. The actual 2nd harmonic operation will start afterwards.

BEAM SYNCHRONIZATION

The J-PARC timing system has definitions, "*scheduled timing*" and "*synchronization timing*". The *scheduled timing* is based on the *50 Hz trigger clock*, and the *synchronization timing* is based on the accelerating RF clock generated by the digital low-level RF of the ring RF systems, not synchronized with the *50 Hz trigger clock*. The repetition rate of the RCS is 25 Hz and the MR runs with the various rates (1/6.0s, 1/3.2 etc.), which are defined by the user's request. The repetition rate is not synchronized with the AC-line frequency, but with the *50 Hz trigger clock* based on the *12 MHz master clock*.

To realize stable beam synchronization, we employ the combination of passive MA cavities, the full digital low-level RF control system and the timing system, which is not synchronized with the AC-line frequency. Thus, the machine cycle can be very accurate and the RF generation is precisely reproducible by the DDS. Moreover, thanks to the stable linac operation and the stability of the bending magnet field, the beam acceleration is done without a radial feedback loop. Practically, the injection frequency value of the MR is set to a multiple of 25 Hz. The purpose is that the injection phase becomes simple and more predictable. A low jitter extraction within 1.7 ns has been achieved. [5]

SUMMARY

In RCS, 200 kW continuous beam operation was started. 400 kW equivalent beam was successfully accelerated in a single shot operation. In MR, 150 kW beam operation was started to the neutrino beam-line in the end of FY2010.

The J-PARC facility was heavily damaged by the great TOHOKU earthquake of March 11, 2011. Fortunately, the damage of the RF devices was small. In MR, the confirmation and the high power examination of the RF systems were completed in June. Toward the J-PARC operation in December 2011, the installation of two 2nd harmonic systems and the construction, which separates the cavity cooling system, are under way. In addition, the core replacement in both the RCS and MR cavities is also scheduled in this autumn.

Thus, cavity maintenance is still needed. However, in view of the stable high intensity beam acceleration, the MA loaded RF system, full digital LLRF and the feedforward system are one of the most reliable components in the J-PARC.

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