PROTON BEAM ACCELERATION WITH MA LOADED RF SYSTEMS IN J-PARC RCS AND MR SYNCHROTRON

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Abstract

J-PARC is a unique accelerator; because magnetic alloy (MA) loaded cavities are employed for the first time in the rf systems of high intensity proton synchrotrons. High field gradients of more than 20 kV/m are achieved covering the frequency range from 0.9 MHz to 3.4 MHz. The peak voltage of 45 kV per cavity is obtained by driving with two 600 kW tetrodes in push-pull. The first high intensity beam acceleration was successfully initiated at J-PARC RCS. Although RCS beam commissioning started with 10 rf systems, instead of 11 as designed, RCS succeeded in the acceleration of an intense proton beam, which is equivalent to 300 kW when operated at 25 Hz. The longitudinal painting based on the simulation with superimposed second harmonics and with phase and momentum manipulations was the key of success. In December 2008, the Material and Life Science facilities started the user operations. During the development stage of the MA cavities, some serious problems such as electrical breakdown on core surfaces occurred. The problems were solved in a short term, and all rf systems were completed on schedule.

INTRODUCTION

J-PARC is a high intensity proton accelerator designed to accelerate more than 10^{14} protons per pulse. The intensity is 100 times higher than that of the 12GeV KEK proton synchrotron. The beam loss budget becomes the key issue. The lattice is designed so as not to cross transition energy during the acceleration. The imaginary gamma transition lattice [1] is the original feature in the 50GeV main synchrotron (MR) lattice design to avoid beam loss, which might happen during transition crossing. The rf accelerating system adopted a digital system for stability and reproducibility. Moreover, the stability of a system was secured without tuning loops. The research and development of the high electric field gradient rf accelerating system for the J-PARC achievement started in 1995 at the KEK Tanashi branch. Especially, J-PARC Rapid Cycling Synchrotron RCS is compact and the free space of the ring is limited, and also the repetition rate is 25Hz. The rf system has to deliver more than 20kV/m field gradient. Moreover, it was necessary to develop a new magnetic material core to match to the large beam pipe, and also to clarify various technical issues like manufacturing a large-scale core and cooling method, etc. A magnetic-alloy material (MA) was the material in place of the conventional ferrite materials, because the MA core has the higher saturation magnetic flux density and a high Curie's temperature. Though the development of MA loaded cavity for J-PARC started in 2000, the project was admitted at once afterwards, and development and construction were advanced in parallel. And, all the accelerating systems of RCS are completed in the summer of 2007. Afterwards, the MR systems are completed according to the MR beam commissioning.

RCS BEAM ACCELERATION

Longitudinal painting is the key issue to accelerate a high intensity proton in RCS. The bunching factor, which is defined as the ratio of the average current divided by the peak current, is required to be 0.4 at injection to alleviate the space charge effect. The linac beam pulse is 500μs at maximum and in case injected at 250μs before the timing of B_{min}. Moreover, the RCS rf clock chops the linac pulse with the duty between 50% ~ 65%, so that the chopped linac beam trains are stacked onto the (slightly) moving rf bucket in each turn. The height of the rf bucket is dp/p ~ 1%. However, the momentum spread of linac beam is small, typically ~ ±0.04%, the linac beams do not match to the rf bucket. The bunching factor becomes peak at every second synchrotron period. In order to increase the bunching factor during the injection and the early accelerating period, the momentum offset injection scheme with superimposed 2nd harmonic voltage is planned.

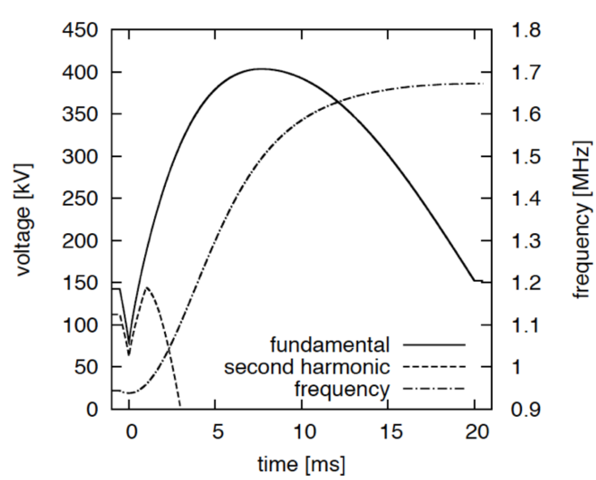

Figure 1: Typical voltage patterns with 2nd harmonic rf in RCS. The 2nd harmonic amplitude is maximum at 1ms, 80% of fundamental rf amplitude [2].

The RCS rf cavity is a broadband system (Q=2), which is able to cover the fundamental and 2nd harmonic frequency band. Therefore, the system can operate the 2nd harmonic rf system for bunch shape manipulation as well as the fundamental rf system for acceleration. The rf signals are superimposed and controlled by the digital low-level rf based on a direct digital synthesis (DDS). The painting experiment was performed comparable to the parameters of the particle tracking calculation, and verified the calculation at the same time.

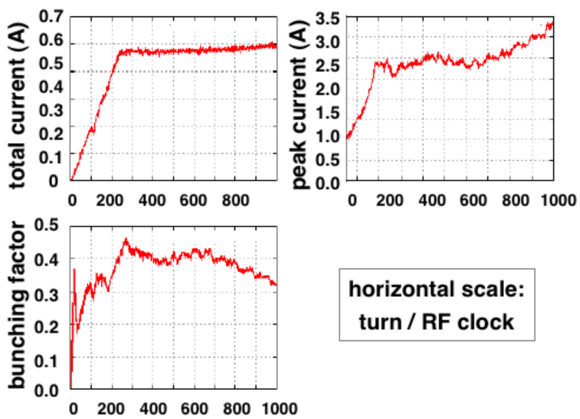

Figure 2: Summary of longitudinal painting in RCS; (upper left) total current, (upper right) peak current of bunch and (lower left) bunching factor; linac 15mA, chopping width 700ns, momentum offset -0.2% at injection and 2nd harmonic phase sweep of 80 degree.

The high intensity trial in RCS has been demonstrated in September 2008. The beam parameters of Linac and the RCS B-field are very stable and reproducible so that the radial feedback is not applied or not needed. And also, the beam loss was able to be minimized during the beam study by using a single shot beam in the beam study.

When longitudinal painting is fully applied, 8.32 x 10^{12} protons are accelerated with no visible beam loss. This intensity is equivalent to 353kW. On the other hand, the intensity is limited to 270kW when the 2nd harmonic voltage is not applied.

50GEV MR BEAM ACCELERATION

The 50GeV MR proton synchrotron has an imaginary gamma transition lattice. The transition energy is not crossed during acceleration. This lattice features in J-PARC high intense MR proton synchrotron. The first beam acceleration in MR was performed with 6.0sec cycle and 2.5sec accelerating periods. The voltage pattern in MR is constant and the amplitude is kept 160kV/turn with the 4 rf systems. In December 2008, 3GeV RCS protons have been successfully accelerated to the present design energy of 30 GeV. The intensity was 4 x 10^{11} protons per pulse. Figure 3 shows the typical intensity signal during the cycle. No visible beam loss is observed on DCCT.

In January 27, 2009, 30GeV protons from the 50 GeV MR were successfully extracted to Hadron Experimental Hall with 3rd resonance extraction scheme and transported to the beam dump. And then, in April 23, 2009, 30GeV protons were successfully extracted with a fast kicker magnet to the neutrino beam line for the T2K experiment.

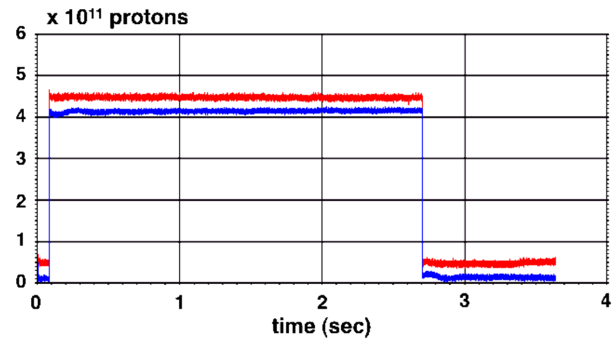

Figure 3: Two different DCCT signals in MR. The step responses of two DCCT's are slightly different.

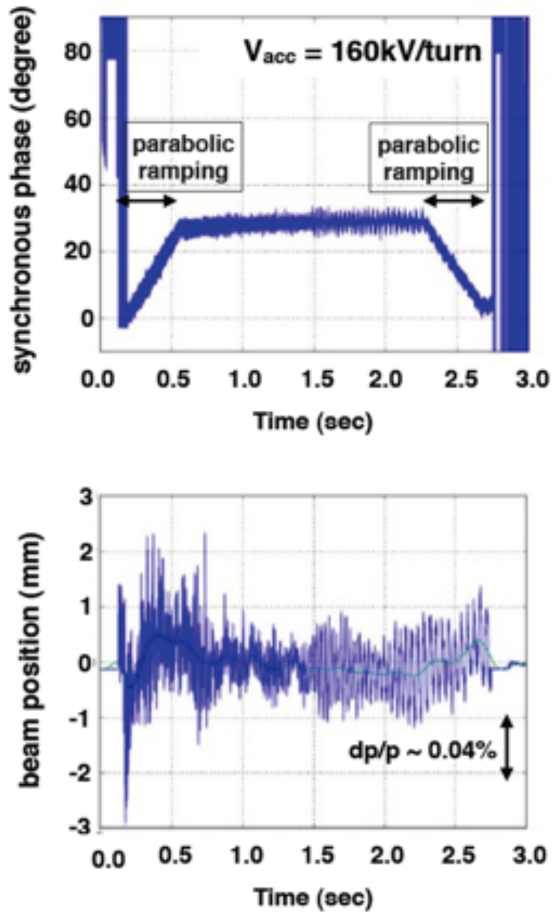

Figure 4: Synchronous phase (upper) and Δ R orbit signal (lower) during acceleration in MR. No Δ R and phase feedbacks are applied.

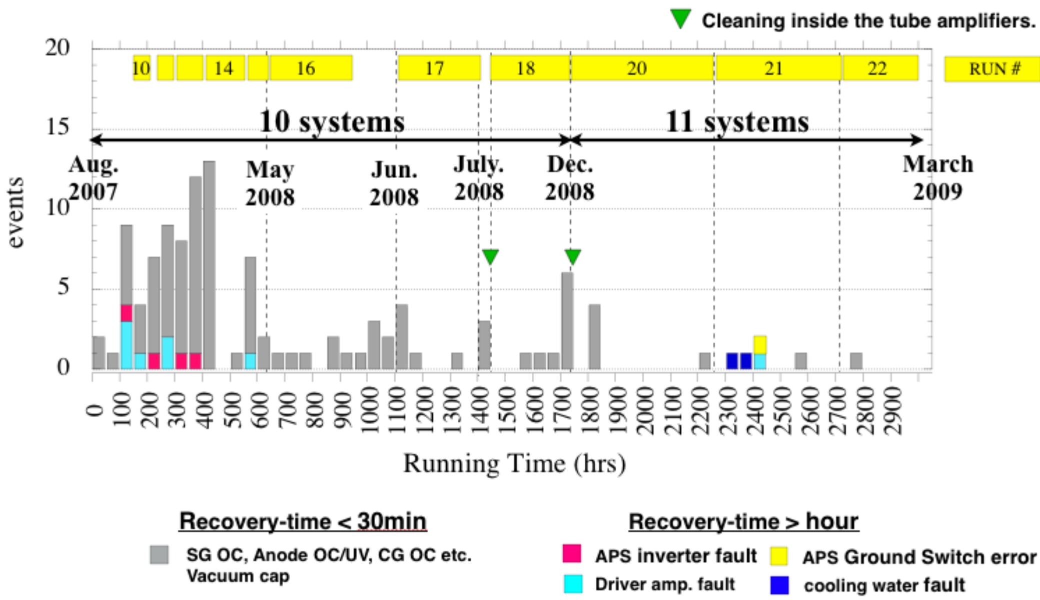

Figure 5: Summary of RCS RF system faults since the systems installed in RCS tunnel.

SYSTEM FAILURES

Total operation times after installations of each RCS and MR system are 3200hrs and 2000hrs, respectively. The number of system failures during the period is 120 times in RCS and 6 times in MR. The major difference of those numbers between the RCS and MR systems is due to the difference of operating point of the tube amplifier. The screen grid voltage in RCS is higher than that in MR. In case of RCS, an interlock of the screen grid/ anode/ and control grid power supplies causes 87% of failures. Especially, dust, moisture and dew inside the tube amplifier trigger sparking. The cleaning inside the amplifier in July and December 2008 seems effective to reduce the failure as shown in Figure 5. The percentage of downtime due to the rf system faults was 3% of total downtime.

CAVITY IMPEDANCE

The 11 RCS cavities and 4 MR cavities are installed and are in operation. In order to check the condition of each system, each cavity temperature and each cathode current of two tetrodes are monitored and recorded during operation. However, it is difficult to observe the change in the impedance of percent order due to the AVC control and the dual harmonic operation. The impedance measurement in the maintenance period that uses the network analyzer is useful as a direct method [4]. During this regular impedance measurement, the impedance reduction was found at one of the 11 RCS cavities. This reduction seems to be starting slowly in August 2008. In December 2008, the impedance dropped down by 5%. More detail impedance measurements were done afterwards. And, we knew that one of the 6 water-tank vessel consisting the cavity had a large impedance reduction. The system was rearranged to 2-gaps instead of 3-gaps and operated to retain the RCS operation in January and February 2009. In March 2009, the cavity was opened to investigate the cores inside and the three damaged cores were replaced with new cores to put the cavity back into the tunnel for the next beam operation in April. The change in impedance originates from the further progressing of the buckling in the core, leading to destruction of the layer structure. The mechanism and the prevention plan of the buckling are being examined.

SUMMARY

In both 50GeV MR and 3GeV RCS, protons were successfully accelerated to the designed energy. And, 30 GeV protons are extracted to the Hadron experimental hall with a 3rd resonance scheme and to the Neutrino line with a fast extraction scheme. In RCS, the longitudinal painting based on the particle tracking was researched, and the agreement with a good outcome of an experiment and calculation was confirmed. Also, in high intensity trial, the equivalent beam power of 350kW was demonstrated successfully.

REFERENCES

[1] S. Machida, et.al, “Lattice Design of JHF Synchrotrons”, APAC98, 1998, KEK Tsukuba, Japan
[2] M. Yamamoto, et.al, “Longitudinal particle simulation for J-PARC RCS”, in this conference
[3] F. Tamura et.al, “Longitudinal painting with large amplitude second harmonic rf voltages in the rapid cycling synchrotron of the Japan Proton Accelerator Research Complex”, *Phys. Rev.ST Accel. Beams, vol.12, 041001 (2009)*
[4] M. Nomura et.al, “Impedance measurements of MA loaded RF cavities in J-PARC synchrotrons”, in this conference