THE STATUS OF THE J-PARC RF SYSTEMS

M. Yoshii*, E. Ezura, K. Hara, C. Ohmori, A. Takagi, M. Toda, K. Hasegawa, M. Nomura, F. Tamura, A. Schnase, M. Yamamoto,
KEK&JAEA J-PARC, Tokai-Mura, Ibaraki-Ken 319-1195, Japan
S. Anami, K. Haga, K. Horino
NAT, Tokai-Mura, Ibaraki-Ken 319-1195, Japan

Abstract

The first acceleration of a proton beam at the J-PARC Rapid Cycling Synchrotron started in October 2007. The R&D for the Magnetic Alloy loaded rf-systems to realize a high field gradient accelerating system for a rapid cycling machine has been initiated in 1995 with the aim of surpassing standard ferrite loaded cavities. The RCS RF system is broadband and designed to cover both the RCS accelerating frequency range and the second harmonic for bunch shape manipulation. The optimum Q value of the RCS cavities is approximately 2. This is realized by combining a high-Q parallel inductor with an un-cut core configuration. The beam commissioning of the 50GeV Main Ring synchrotron started in May 2008. Acceleration and slow-beam extraction are planned for December 2008. In case of the MR RF system, the accelerating frequency swing is small. The Q-value in the order of 20 has been selected to reduce transient beam loading due to the multiple-batch injection scheme. The MR RF cavities realize the Q-value by a cut-core configuration. The details of the RF systems and the results of beam accelerations are summarized.

INTRODUCTION

The ring RF system is a key component in the J-PARC synchrotrons. A high field gradient system is required. The Magnetic Alloy (MA) material is considered as the modern cavity material being taken instead of the conventional ferrite material [1]. It has a high saturation magnetic flux density (Bs) > 1.3T and a high Curie's temperature (>500°C). Non-linear or catastrophic phenomena are not observed even under high electromagnetic field. The MA material has a low-Q but high magnetic permeability. The shunt impedance is high and stable at high electromagnetic field. We can realize stability and reproducibility by combining a full-digital LLRF with a passive MA loaded system. The magnetic alloy is made of a wound thin metal ribbon. Large cores are available, which could fit to the large beam pipe of RCS. The material is electrically conductive. Insulation inside the cavity and effective cooling are issues to be solved. Also, the recent ideas to control the Q-value of the cavity have been proposed and verified.

RF SYSTEM

General

The RCS is a rapid cycling synchrotron with 25Hz repetition. The maximum B-dot reaches 70 Tesla/sec. The peak voltage of 450kV is required for stable acceleration. Also, the longitudinal bunch formation is essential to alleviate strong space charge in both RCS acceleration and 50GeV MR injection.

Table 1: The design parameters of RF Systems

	3GeV RCS	50GeV MR
Energy (GeV): Inj.	0.181	3
Ext.	3	50
γ_t	9.14	-31.6*1
Cycle or period	25Hz	3.64 sec
Number of proton	8.3×10^{13}	3.3×10^{14}
Acc. Voltage (fund.*2)	450kV	280kV
Max. $\phi_{synchronous}$	45 degree	28 degree
Circumference (m)	348.333	1567.5
RF harmonic (fund.)	2	9
RF frequency (fund.) Inj. /Ext.	0.938 / 1.67MHz	1.67 / 1.72MHz
Number of cavities	11 (+1 spare)	6 (+1 spare)
Voltage per cavity	41kV	47kV
Quality factor	2	20~30

*1: imaginary transition energy
*2: fund. = Fundamental

The cavity bandwidth was designed to cover the fundamental (*h*=2) and the second harmonic (*h*=4) frequencies. To control the incoherent tune shift growth, the longitudinal bunch shape manipulation is the way to solve the problem. The corresponding optimum Q-value is set to 2. And, the combined RF signal of a fundamental and 2nd harmonic will be fed into the same cavity. Two longitudinal functions of "beam-acceleration" and "bunch-manipulation" are combined in the RCS RF system.

The 50GeV Main synchrotron is a slow ramping machine. The cycle is 3.64s. The peak accelerating voltage requires 280kV at maximum. Because of the multiple-batch injection scheme and the long injection porch, the periodic transient beam loading should be taken into account. This effect becomes most severe when the injected beams fill half the MR buckets. Therefore, the optimum Q-value for MR RF system is set to 20-30. In case of MR, the 6 accelerating systems and the 3 second harmonic systems are separately designed. The basic designs in two different systems are the same; the only difference is the number of capacitors located on each of three gaps for tuning to the resonant frequency.

Optimizing Q-values of cavities

The cut-core configuration allows changing the effective quality factor of the cavity widely, with keeping the shunt impedance. The toroidal-shaped MA cores are cut in two halves and located in the cavity with the certain air gap. The air gap along the magnetic path increases the magnetic resistance. The resulting inductance of the cavity becomes small due to the gap distance. This is the principle of the cut-core configuration. In case of the RCS cavity system, the original idea was this cut-core configuration to realize Q=2. However, the air gap distance is small around 0.8mm, which becomes comparable to the mechanical tolerance. Another configuration by adding an additional high-Q inductor in parallel has been developed to set the cavity Q-value [2].

In the case of the MR system, the target Q-value is 20~30. The air gap distance of cut cores becomes 10mm in this case. The original cut-core configuration was adopted. The cut core surfaces are finished with diamond polishing to keep good electrical isolation [3].

Table 2: The Parameters of RF Cavity

	RCS cavity	MR cavity
MA core		
Size (outer/inner/thick: mm)	850/375/35	800/245/35
Number /cavity	18	18
Type	uncut	cut
Cavity		
Core Inductance (μH)	57	1.56
Ext. Inductance (μH)	12.6	N/A
Ext. Capacitance (pF)	200	5000
Resonance (MHz)	1.7	1.72
Cooling water (L/min)	250	250
Quality factor	1.76	23

Cavity cooling is the key issue to realize a high gradient cavity. The RF power dissipation per core reaches 5kW for the RCS cavity and 9kW for the MR one. For effective core cooling, the most efficient cooling method, "*direct water cooling*" has been adopted. Each core is coated with an epoxy resin to prevent corrosion. However, because the cut surfaces of MR cut-cores are smooth and have mirror like quality, coating becomes more difficult. Therefore, demineralized cooling water with reduced dissolve oxygen is used.

BEAM COMMISSIONING

The beam commissioning of the Linac had already started in December 2006. The linac beam had been well tuned. When the RCS beam commissioning started, the linac beam had proven stability and reproducibility. The peak intensity of the Linac can be set to 5mA, 10mA or 30mA. The pulse width (=macro pulse width) is also possible to change within 500μs. The injection scheme from Linac to RCS is "chopped beam injection" instead of "adiabatic capture" [4]. The longitudinal painting with momentum and phase offset is available to minimize losses at the early acceleration. The beam studies at RCS have been done with DC mode (non-acceleration) and 25Hz AC acceleration mode [5]. The Linac beam momentum and the RCS Bending-field are so stable that the longitudinal beam feedbacks of Δr and $\Delta\phi$ are not necessary. The accelerating frequency pattern was defined from the BPM positions without the automatic orbit correction.

The 5 MR cavities with cut-cores were tested for more than 300hrs at the test stands in KEK and JAEA, as well as the RCS cavities. One system was kept in the test stand for further test and the rest of 4 cavities were installed in the MR tunnel afterwards (Figure 3). The first beam commissioning started with DC storage mode in May 2008. The voltage per turn is 160kV. Figure 1 shows the mountain view-plot of bunch from the RCS.

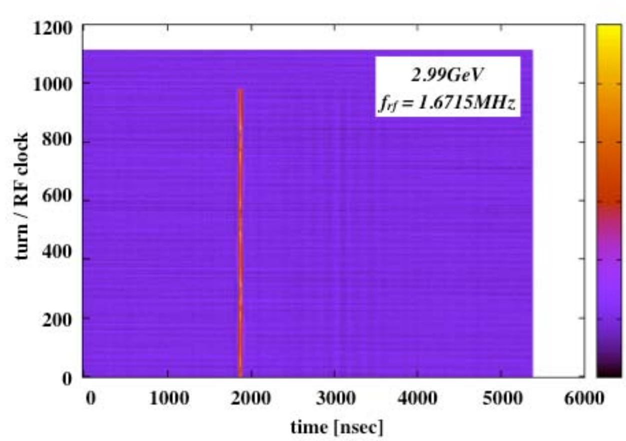

Figure 1: Mountain view-plot during MR injection, (Revolution period is about 5.3μsec)

As for preliminary tuning, the injection frequency was set within 0.04% of momentum error. In case of RCS, it was difficult to determine the right voltage seen by the circulating beam as function of the synchrotron frequency, because the RF voltage contained the 3rd harmonics. In case of MR, the voltage waveform consists of a single harmonic because of high cavity Q-values of 22. Here the synchrotron frequency gives more reliable voltage prediction. Figure 2 is a preliminary measurement of the synchrotron frequency as a function of voltage per turn. The result was consistent with the expected values.

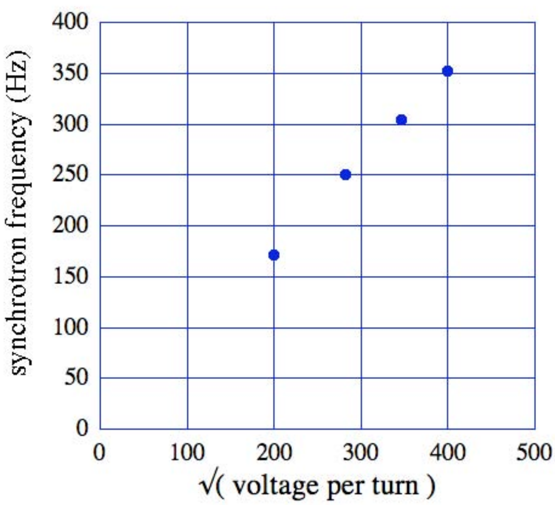

Figure 2: Synchrotron frequency vs. MR RF voltages

OUTLOOK

The 10 RCS cavities and the 4 MR cavities are installed. The systems have been working well without problems. The beam commissioning of RCS and MR has also successfully been initiated. The Linac beam and the RCS magnets are stable. The studies with one-shot beam allow the effective beam commissioning without unnecessary beam loss. The MA RF system has no-tuning control, i.e. the system works as a passive load. The combination with full digital LLRF has great advantage. The beam acceleration in RCS has been performed without any beam feedback. And, the beam intensity of 10^{13} per pulse has already been demonstrated. The MR beam commissioning has started with no-acceleration. Acceleration and slow-beam extraction are planned for December 2008. However, for intended program in December, the basic parameters will be intensively studied in this May and June 2008.

As for the J-PARC roadmap, the user operation in the MLF (Material and Life science Facility) and the neutrino experiments with 30GeV proton will start in April 2009. And also, the Linac energy upgrade will be completed by FY2012. In FY2008, the 11th RCS system and the 5th MR system are prepared for stable operation in FY2009. The completion of the whole system (1 RCS system, 2 MR fundamental + 2 MR 2nd harmonic systems) must finish by the end of FY2011.

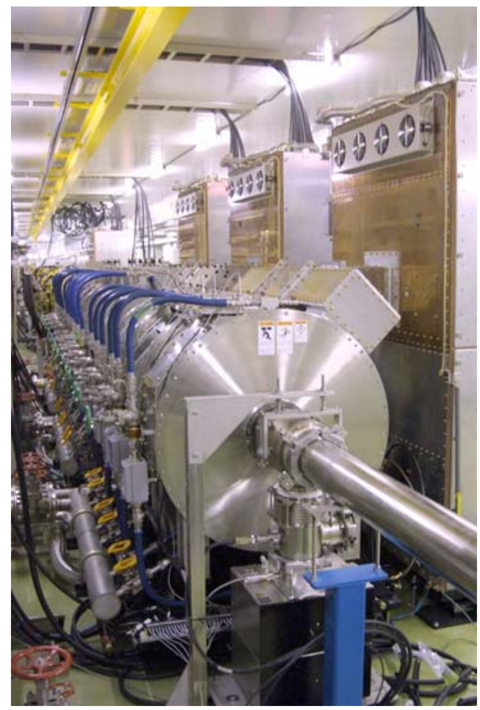
Figure 3: The 4 MR Cavities and amplifiers in the MR tunnel

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