PRESENT STATUS OF J-PARC RING RF SYSTEMS

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Abstract

The accelerator of the J-PARC complex consists of the 400MeV (initially 181MeV) linac, the rapid cycling 3GeV Synchrotron and the 50GeV main Synchrotron. To accelerate an ultra-high intense proton beam, the synchrotrons require a high field gradient RF system (~25kV/m). Alleviating space charge effects is a key issue for minimizing beam losses during a cycle. Longitudinal bunch manipulation is also considered as well as acceleration. Magnetic alloy loaded cavities are the most practical choice for the J-PARC. Such system provides high field gradient, and broadband behaviour. It is a stable passive system without tuning control. Multi-tone signals can be fed into the same cavity for acceleration and bunch manipulation. However, the harmonics of circulating beam current within the cavity bandwidth must be taken into account. A feed-forward scheme is used for compensating beam-induced voltages. The low level RF system is fully digital to provide precise control. The specification is based on high reliability and reproductivity. The design consideration of the whole RF system will be described and the current status presented.

INTRODUCTION

The J-PARC beam commissioning is planned to make three major steps to reach the beam full intensity. The early steps, called "Stage-I & II", start with the linac energy of 181MeV. The target beam power will be 100 kW during this period. Beam commissioning in MR is going to be started at "Stage-II". In case of 181MeV injection, the intensity in RCS is limited to 60% of the design value; even so, an alternative scheme has been considering to keep the original beam intensity in MR.

LONGITUDINAL SCHEME

Beam loss due to space tune shift is the remaining issue after the beam is accelerated successfully. Longitudinal manipulation is very important to manage the incoherent tune shift.

Injection into Rapid Cycling Synchrotron (RCS)

The linac beam pulse is formed into macro-pulses by the choppers. The time structure of macro-pulse is synchronized to the accelerating frequency of the RCS RF system. The typical macro-pulse width is 56% of the RF period. The beam is injected with adequate momentum offset, to make a slightly hollow bunch (Figure 1). A second harmonic potential is also added simultaneously to reduce the peak beam current [1].

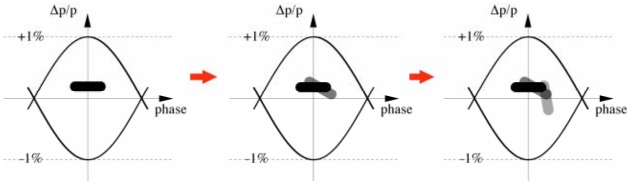

Figure 1: Longitudinal macro-pulse capture in RCS.

Injection into Main Synchrotron (MR)

Two bunches in RCS will be transferred simultaneously to the 50 GeV MR. Since the circumference ratio of RCS and MR is 2:9, the extraction frequency in RCS must be exactly the same as an injection frequency of MR. In order to realize such a synchronization condition between two synchrotrons, a precise machine cycle, which is based on a non-50Hz-line-synched timing system, and a stable magnet field pattern are required. The synchronization process has to be started several milliseconds before extraction, because of the very low synchrotron frequency near extraction. The RCS beam is supplied for the "Neutron target" of Material and Life Science (MLF) users as well as the MR. On the other hand, the beam extraction for MLF user is carried with scheduled every exact 40msec timing, because of the high performance "Fermi-chopper"[2].

The space charge tune shift in MR injection is more severe than that in RCS. The longitudinal beam distribution must be well manipulated at RCS extraction; i.e. before MR injection. A second harmonic system (h=4) is necessary to realize the required bunching factor. However, the matching condition of transferred beam into MR must be satisfied at the same time.

Table 1: Major Parameters

	RCS	**MR**
Energy (GeV)	0.181 ~ 3	3 ~ 50
γ_t	9.14	j36.1 *1
Circumference (m)	348.3	1567.9
Intensity (ppp)	8.3×10^{13}	3.3×10^{14}
Cycle/period	25Hz	3.64sec
Acc. Voltage (kV)	450	280
Harmonic number*2	2	9
RF frequency (MHz)	0.938~1.67	1.67~1.72

*1: imaginary energy, *2: fundamental RF

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Alternative scheme for recovering MR intensity

In the original scheme, two RCS bunches are transferred four times into 8 of 9 rf-buckets in MR, where one empty bucket is reserved for rising space of an extraction kicker. When the intensity in RCS is not recovered, however, one bunch is transferred fifteen times into 15 of 18 rf-buckets in MR for recovering MR intensity. In this case, the tuning frequency for MR rf-cavity has to be changed to 3.44 MHz (h=18) by replacing the external tuning capacitor for the cavity. And, single bunch beam acceleration is required in RCS with the h=2 RF system.

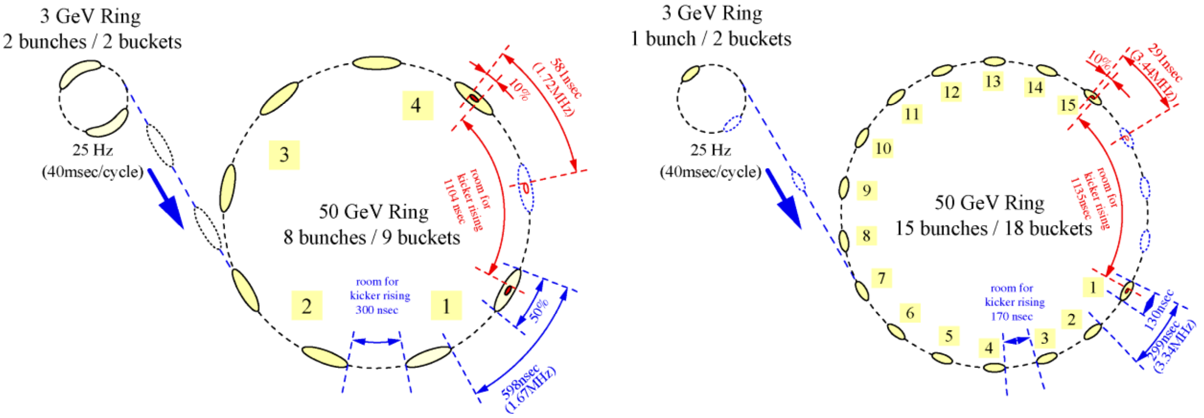

Figure 2: Schematic drawings of "Original" (left) and "Alternative" (right) beam transfer scheme between the RCS and the MR.(drawn by Y.Shirakabe, J-PARC kicker Group)

HARDWARE REQUIREMENT

The RF systems for both synchrotrons are designed for "flexibility" in hardware and associated low-level RF control. We describ briefly about the cavity system, RF source and its DC power supply and low level RF system.

Cut-core cavity

The cavity requires a high field gradient of ~25kV/m. Magnetic alloy materials are employed for loading the cavity, instead of conventional ferrites. The bandwidth of the RCS system is 0.94MHz – 1.67MHz at h=2. Optimum un-loaded Q for the RCS system is Q=2. The cavity is driven by the combined rf-signal of a fundamental (h=2) and the second harmonic (h=4). On the other hand, the bandwidth of MR system is 1.67MHz – 1.72MHz for h=9. The frequency changes only 3% in this case. The un-loaded Q is not necessary to be low, and from the point of view of transient beam loading the moderate Q is 10-20 chosen. "Cut-core" configuration is the way to change an effective un-loaded Q value of the cavity. The distance of air gap at the cut-core changes the magnetic resistance along the magnetic path. The required Q-values for RCS and MR cavities are Q =2 and Q=15 at 1.7MHz, respectively. The corresponding air gap distances to achieve the Q-values are 0.8mm in the RCS cavity and 10mm in the MR.

Surface coating on a magnetic alloy core is very important process to keep the mechanical strength during the cutting process and for corrosion protection. The cavities are cooled by high-purity de-mineralized water, which is called "direct cooling" cavity [4]. However, it is important to prevent water from penetrating into the core layer. Water-jet machining was used for cutting the cores, because of inexpensive running cost and only small damage to the electric isolation on the cutting surface of the magnetic alloy layers. But, the roughness and electrical breakdown on cut-surface becomes an issue. Particularly for RCS cavity, machining accuracy reaches to the limit of air gap distance without coating. The "Grind-stone" cutting method was developed and will replace the "water-jet" cutting to solve the problems [5].

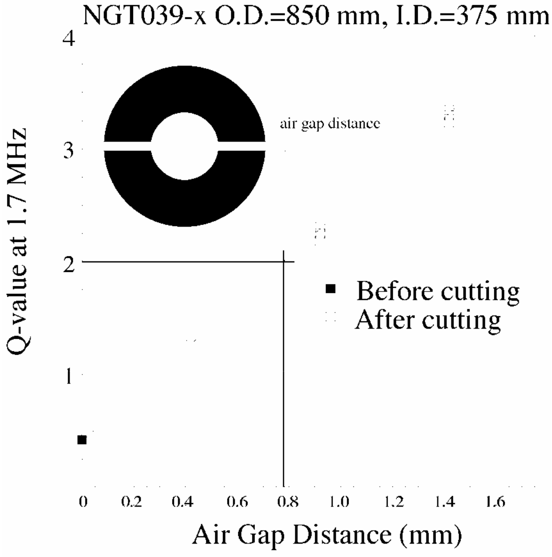

Figure 3: Q-value of cut core as a function of air gap distance.

Low level radio-frequency control (LLRF)

A MA loaded cavity system is a very linear and passive system. Particularly no-tuning loop is necessary due to broadband characteristics. The LLRF based digital signal processing is suitable for such the MA loaded system. The main functions of LLRF [7] consists of

- Precise RF signal generator based on Direct Digital Synthesis (DDS).
- Amplitude control feedback loop (AVC)
- Beam-phase control feedback loop ($\Delta\phi$)
- Radial control feedback loop (Δr)
- Multi-harmonic feed-forward beam compensation

The feed-forward is essential to compensate heavy beam induced voltages. In RCS, h=1,2,3,4,5,6 harmonics of beam current signals are fed into each cavity to cancel the voltage distortion [6]. And, in case of MR, adjacent three components of rf-harmonic are taken into account.

In the digital filtering process for separation of the harmonics, a short delay time is an important issue to realize stable loop operation. For example, a cascaded CIC filter with coefficients tracking the revolution frequency is considered as alternative to a standard FIR filter to reduce the delay to 50 percent [3].

Power source and DC power supply

Final stage amplifier consists of two tetrodes operated in class-AB push-pull, grid-driven cathode-grounded mode. The amplifiers are located adjacent to the cavities in the tunnel. And, the tetrode is commercially available with max. Plate dissipation of 600kW, which is either TH558 or 4CW500,00GB.

The push-pull amplifier operates in two- (or multi-) tone drive. An all-pass network is used on the control grid circuit to realize a wide bandwidth. Adjustments for symmetrical operation need more systematic analysis with the real system [8].

Figure 4: Inside of 1.2MW final stage amplifier

The IGBT inverter DC power supply is designed for 1.2MW Anode DC power. It combines “low plate voltage ripple and sag-drop”, and “reliable operation”. The power supply has 15- IGBT units connected in parallel. The maximum switching frequency is 31.2kHz. The fast voltage feedback and current feed-forward controls allow low voltage ripple, a fast crowbar-less power cut-off to protect the tube amplifier and redundancy. The achieved “voltage ripple” and “sagging-drop” are ±0.2% and ±1%, respectively. The noise and switching frequency components are well separated from the synchrotron frequency bands (6kHz~400Hz:RCS, 20Hz~600Hz:MR).

SUMMARY

The 11 RF systems in RCS and the 6 in MR take care of beam acceleration and 2.8 MW and 1.5MW peak beam power as well as accelerating power. Total accelerating voltages are 450kV and 280kV at peak, respectively. High field gradient accelerating systems are required, and the magnetic alloy loaded cavities are chosen to realize this requirement. Un-loaded Q-values of cavities are controlled by “Cut-core configuration”. Optimum Q = 2 for RCS, and Q = 10~20 for MR. In RCS, the system provides “combined function”, i.e. it is used for beam acceleration and longitudinal manipulation. Dual harmonics (h = 2) and (h = 4) signals are fed simultaneously into the RCS RF system.

The low level RF is realized by FPGA based digital signal processing. Precision is guaranteed by DDS based RF signal generation. A feed-forward system is considered as an essential method to compensate heavy beam loading.

Anode DC power supply is developed based on IGBT inverter/converter technique. Such pulse mode power supplies realize low voltage ripple, redundancy and a fast power cut-off to protect a tube amplifier. The final stage amplifier has two tetrodes, which operate in class-AB push-pull. The drive RF signal for the amplifier is basically multi-harmonic signal. It is important to optimize the operating condition of each tetrode under multi-tone drive in the push-pull amplifier.

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