ACCELERATION OF HIGH-INTENSITY PROTONS IN THE J-PARC SYN-CHROTRONS

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Abstract

The J-PARC consisting of the 181 MeV Linac, the 3 GeV rapid cycling synchrotron (RCS) and the 50 GeV main synchrotron (MR), is the first high intensity proton synchrotron facility to use the high field gradient magnetic alloy (MA) loaded accelerating cavity. MA is a low-Q material. However, because of the high permeability and the high saturation magnetic flux density, the MA cores are the only materials to realize the required gradient. The MA loaded cavity can be considered as a stable passive load. No tuning control is necessary. 11 RF systems are operational in the RCS, and 8 RF systems in the MR. In addition, the RCS RF systems are operated in a dual harmonic mode to perform the acceleration and the longitudinal manipulation of the high intensity beam in the available space in RCS. Beam loading compensation is an important issue. The feed-forward method using the RF beam signals from the wall current monitor has been established. The J-PARC synchrotrons realize stable, reproducible and clean acceleration of high intensity protons. A transition-free lattice and a precise digital timing system asynchronous to the AC-line are the distinctive features, which enable this achievement.

INTRODUCTION

The J-PARC facility is a versatile science facility using the secondary particles like neutron, neutrino, Kaon, pion, etc. produced by an intense proton beam. The Linac and the RCS run at 25 Hz. The 3 GeV proton beam of 8.3×10^{13} protons per pulse from the RCS, which corresponds to the designed output beam power of 1 MW, is sequentially delivered to the MLF and the MR. Consideration of beam loss during accelerating in the synchrotrons is one of the important issues. The intensity handled at the J-PARC is 100 times higher than the intensity of the KEK-PS that we have ever experienced. A transition free lattice is introduced in designing the two synchrotrons [1]. The Fermi chopper has large rotational momentum inertia. The time-jitter of the extracted proton beam is required to be less than 100 nsec. Scheduled extraction to the MLF from the RCS has been considered, too. To realize the requirements, the J-PARC timing system is based on the 12 MHz precise external clock, which is asynchronous to the 50 Hz AC-line.

The J-PARC beam commissioning has been started with the lower Linac energy of 181 MeV. In case of 181 MeV injection, the output beam power in the RCS is limited to 60%. Until now, a 420 kW equivalent beam was extracted from the RCS as a high intensity trial and the 275 kW beam is steadily delivered to the MLF.

The nominal machine cycle of the MR is 6.0 seconds for the Hadron experiment (SX: slow beam extraction by using a third-integer resonance) and 2.56 seconds for the Neutrino experiment (FX: fast beam extraction by using the fast kicker magnets). The MR cycle for T2K experiments has been set 30 % shorter than the original 3.64 seconds to obtain the maximum output beam power. On 30th May 2012, the number of accelerating particles per pulse exceeded 114 Tera (114×10^{12}) protons at a high intensity trial run. The output beam power corresponds to 213 kW.

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Table 1: Major Parameters

	3GeV RCS	MR
Energy (GeV)	0.181 – 3	3 – 30
γ_t	9.14	j31.6 *1
Circumference (m)	348.333	1567.9
Intensity (ppp) *2	2.5×10^{13} (8.3×10^{13})	1.4×10^{14} (3.3×10^{14})
Cycle/period	25Hz	2.56 s (FX) 6.00 s (SX)
Acc. Voltage (kV)	400	280
RF harmonics	2	9
No. of RF stations	11 (12)	9
Voltage per cavity	45 kV	45 kV
No. of gaps	3	3
Cavity length (m)	1.996	1.846
Q-value	2	22
Cavity Impedance per each gap	890 Ω	1100 Ω

* Numbers in ( ) are the design values.
*1: imaginary energy
*2: (upper) achieved value and (lower) designed value
FX: Fast extraction, SX: Slow beam extraction

RF SYSTEMS

The RCS and the MR each have a three-fold symmetry lattice. One of three long straight sections is assigned for the location of the RF cavities. There are 12 and 9 spaces for the RF systems of the RCS and the MR, respectively. The beam commissioning has been started at the RCS in 2007 with four RF systems and at the MR in 2008 with the four RF systems and the system has were upgraded every year.

The RF systems for the J-PARC synchrotrons provide a high accelerating gradient (more than 20 kV/m). Magnetic alloy (MA) cores were the only material, which could realize the required accelerating voltages in the

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available space. Each MA core itself is a low Q material. The MA loaded cavities show a wideband impedances. Because of their high saturation magnetic flux density and high Curie's temperature, the RF cavities behave as a stable passive load. No tuning control is necessary. Then, the Low Level RF (LLRF) control loops become simple. These features give a great advantage for the LLRF stability, contributing to stable high beam power operation. For J-PARC, the MA loaded system and the high quality digital LLRF are the best combination to allow precise and reproducible longitudinal control.

Full Digital LLRF

The LLRF control system is fully implemented by FPGA digital circuits. The RF generation is based on the Direct Digital Synthesis (DDS) with a frequency accuracy is 10^{-7}. The LLRF module generates an accelerating frequency and two other harmonics by multiplying the revolution frequency, i.e. h=2, 4, 6 for the RCS and h=8, 9, 10 for the MR. The pattern sampling clocks are 1 MHz and 200 kHz, respectively. Three harmonics are completely synchronized and used for driving the cavity as well as the IF signals for I/Q signal processing. The patterns (amplitude, phase, frequency) are precisely reproducible.

The accelerating RF frequency in the RCS varies from 0.938 MHz – 1.67 MHz. The optimum Q-value of the RCS cavity is 2 so that the cavity bandwidth covers the frequency ranges of both the fundamental and the 2nd harmonics. The RCS systems are operated with a dual harmonic mode. The combined RF voltage allows longitudinal bunch shape manipulation as well as beam acceleration efficiently. On the other hand, the accelerating RF frequency in the MR changes about 3% from 1.67 MHz – 1.72 MHz. The optimum Q-value of the MR cavity is around 25 in consideration of the transient beam loading during the long multi-butch injection from the RCS [2]. The cut core configuration has been used to optimize the cavity Q-value [3].

The accelerating voltage patterns are initially based on the calculation code RAMA [4]. Since the RCS RF systems are operated with a dual harmonic mode, the 2nd harmonic voltage pattern is calculated by the particle tracking code. The RF signals are superimposed at the LLRF and fed into the cavity. The painting experiment was performed comparable to the parameters of the particle tracking calculation to verify the calculation.

ACCELERATION

Longitudinal Painting

In the RCS, the bending magnetic field is an almost sinusoidal wave. The 500 µs Linac beam pulse is injected at 250 µs before the timing of B_{min}. In addition, the RCS RF clock chops the Linac pulse with the duty of ~ 60%, so that the chopped beam trains are stacked onto the slightly moving RF bucket in each turn. The momentum spread of Linac beam is typically ~ ± 0.03 % and small compared to the RCS RF bucket height (~1%). During the bunching process, the bunching factor, defined by the ratio of the average current divided by the peak current, becomes peak at every second synchrotron period. The bunching factor must be large (> 0.4) enough to alleviate the space charge effect during the first several ms of the RCS injection period. Longitudinal painting has been applied by using the momentum offset injection scheme with superimposed 2nd harmonic voltage (Fig. 1) and phase modulation (Fig. 2) [5].

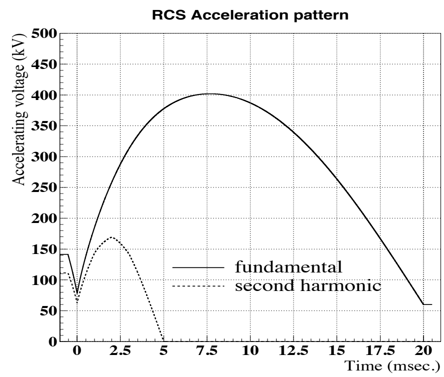

Figure 1: Typical voltage patterns with 2nd harmonic rf in the RCS. The 2nd harmonic amplitude is maximum at 3 ms, 80% of fundamental rf amplitude.

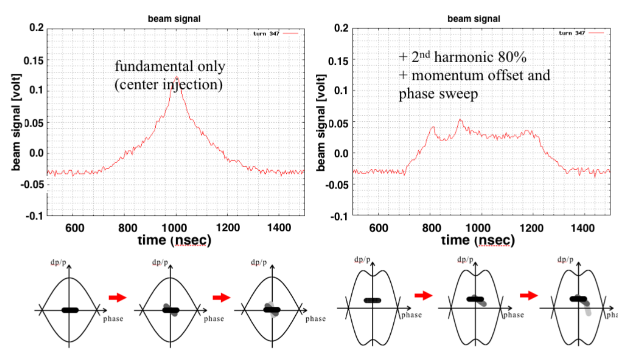

Figure 2: Longitudinal painting with 2nd harmonic RF in the RCS injection; (left) center injection with fundamental RF only, (right) full painting condition with 2nd RF.

Synchronization

In every 40 ms of the RCS cycle, two bunches in the RCS are injected simultaneously into the MR. Four RCS cycles will allow filling the 8 MR RF buckets. Hence, one empty bucket in the MR is used for raising the fast extraction kicker magnets. Since the orbit control loops are off in both the RCS and the MR, the phase advances in the RCS and the MR are constant between cycle to cycle. The MR injection frequency is chosen as an integer multiple of 25 Hz at the most nearest frequency to the RCS extraction frequency. When the frequency can be divided by 25, the phase advance ($2\pi\ f_{RF} \times 40$ ms) between every injection becomes the same. The phase matching for the synchronization in the RCS also becomes easily predictable. Scheduled extraction from the RCS can be realized in this way. The non AC-synched timing system greatly simplifies the synchronization between two synchrotrons as

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well as scheduled extraction for the “Fermi-chopper” with a very low time-jitter within 1.7 ns [6].

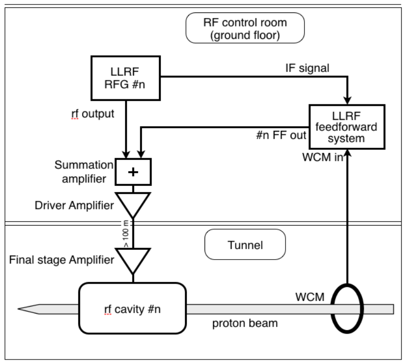

Figure 3: Schematic view of the feed-forward system, the feed-forward system is performed for each cavities.

Multi-harmonic RF Feed-forward System

The multi-harmonic digital RF feed-forward system has been developed to compensate the beam induced wake voltages on each of the cavities (Fig. 3). Three harmonics, h=2, 4, 6 for the RCS and h = 8, 9, 10 for the MR are considered in the feed-forward system. The feed-forward system generates a compensation signal for each harmonics by analyzing the wall current monitor signal. The digital I/Q signal processing is used. I/Q data (gain and phase) for each harmonics depends on the transfer function of each of the RF systems. Since the transfer function of final stage amplifier has a slight output power dependence, the commissioning of the feed-forward system has been performed for each of the cavities with a high intensity proton beam of 2.5×10^{13} ppp corresponding to 300 kW equivalent RCS beam. The impedance seen by the beam has been greatly reduced by the feed-forward (Fig. 4) [7].

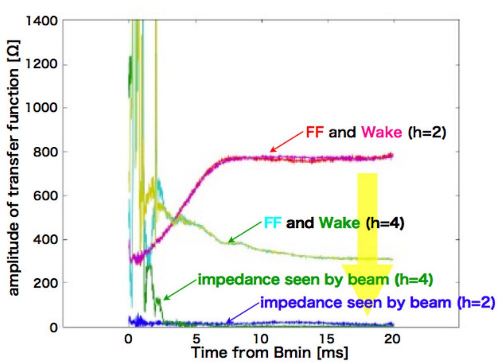

Figure 4: Comparison of the time-domain impedance seen by the beam. (in case of the RCS cavity No.1).

SUMMARY

Transition free lattice design, non AC-synched timing system and the magnetic alloy loaded RF system are the major features of the J-PARC synchrotrons. We have realized a high field gradient RF system with the MA cores. The RF systems could achieve the required accelerating voltage in the available space. The MA loaded cavity has a wideband frequency response and behaves as a passive load. No tuning system is provided. The beam is accelerated without a radial feedback, owing to the stability of the Linac energy and the RCS and the MR bending fields and the accuracy of RF frequency generated by the DDS. The beam orbit and the longitudinal bunch shape are reproducible from cycle to cycle. A very low jitter extraction within 1.7 ns is achieved from the RCS.

The RCS RF systems are operated in a dual harmonic mode to perform the acceleration and the longitudinal manipulation of the high intensity beam in the available RCS space. Applying the large amplitude second harmonic RF during the injection period, the bunching factor is efficiently improved.

The multi-harmonic RF feed-forward has been developed and employed for the beam loading compensation in the RCS and the MR. The feed-forward system takes care of three harmonics of h=2, 4, 6 for the RCS and of h=8, 9, 10 for the MR. The impedance seen by the beam was successfully reduced by > 20 dB.

The space charge tune shift during the MR injection is more severe than that in the RCS. The longitudinal beam distribution must be already well manipulated at the RCS extraction, i.e. before the MR injection. A second harmonic system in the near RCS extraction is necessary to enlarge the bunching factor for the MR. However; the matching condition of transferred beam into the MR must be satisfied at the same time. More beam study and particle tracking analysis are necessary.

In JFY2013, the J-PARC Linac energy is going to be upgraded to the original design value of 400 MeV. And, the 12th RCS cavity will also be installed in summer 2013 toward 1 MW beam operation in the RCS. An issue of limitation in the output beam will be cleared.

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