STABILIZATION OF BEAM EXTRACTION TIMING IN J-PARC RCS

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Abstract

The extracted beams from the rapid cycling synchrotron (RCS) of J-PARC are delivered to the Materials and Life Science Facility (MLF) and the MR. The repetition rate of the RCS is 25 Hz and four beam pulses are for the MR and the other 87 pulses are for the MLF. Stable beam timings are required for both of the destinations. In case of the MLF, the beam has to be synchronized to the Fermi chopper, which has a tolerance of a few 100 ns. In case of the MR, the beam must be injected to the proper RF bucket with a precise phase. To realize the stable beam timing, we employ the non-AC-line synchronized timing system. Also the magnetic-alloy accelerating cavities and the full digital low-level RF control system are the keys for the precise beam phase control. We present the preliminary results of the beam stability measurement.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) [1, 2], consists of three accelerators; the linac, the rapid cycling synchrotron (RCS), and the main ring (MR). The ring parameters of the RCS is shown in Table 1. The proton beams are accelerated from 181 MeV to 3 GeV in 20 ms. The repetition rate is 25 Hz. The destinations of the extracted beams from the RCS are the Materials and Life Science Facility (MLF) and the MR. The destinations are switched in the accelerator cycle. For example, four beam pulses are injected to the MR and the other 87 pulses are delivered to the MLF.

The Fermi chopper spectrometer is a key component of the MLF. The Fermi chopper is a rotating iron with a fast rotating speed, in the order of 500 Hz to 1 kHz. To realize a high energy resolution and an efficient use of the neutrons, the chopper and the proton beam from the RCS must be synchronized; the tolerance is only 300 ns [3]. Because the Fermi chopper has a large inertial moment, it is difficult to change quickly the rotating phase. Thus, the extracted beam timing must be very stable and must have low jitters.

In case of the MR, we employ the bucket-to-bucket transfer method. The harmonic number of the MR is 9. To fill the eight RF buckets in the nine buckets, four RCS cycles are used. The bunches must be injected into the proper RF buckets. Also, a precise phase control is required to avoid the dipole oscillation in the MR.

Therefore, a stable timing of the extracted beam from the RCS in both cases of the MLF and the MR. The J-PARC accelerator complex is operated without synchronization to the AC power line (50 Hz), which has frequency variation in the order of 0.1%, the complex is operated with a master clock generated by a high quality synthesizer. Also we the magnetic-alloy (MA) accelerating cavities and the full digital low-level RF (LLRF) control system makes the precise and reproducible beam phase control possible.

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Table 1: Parameters of the J-PARC RCS

circumference	348.333 m
energy	0.181–3 GeV
accelerating frequency	0.938–1.671 MHz
harmonic number	2
repetition	25 Hz
cavity Q-value	2

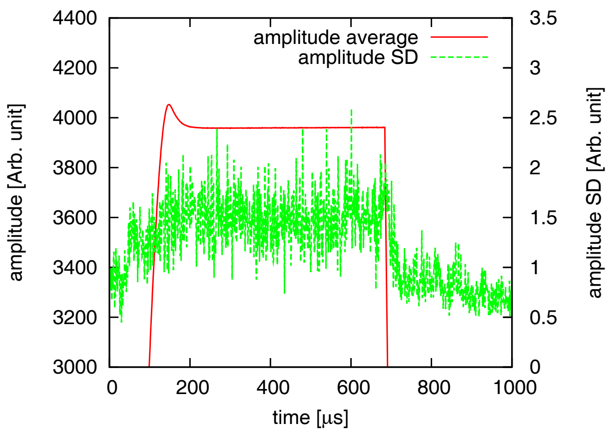
BEAM TIMING STABILIZATION

Non-AC-line-synchronized Timing System

As described in the introduction, we employ a non-AC-line-synchronized timing system. In the timing system [4], three signals (12 MHz master clock, 25 Hz “trigger clock”, and “type” code, which contains the information of operation during the next 40 ms) are generated in the CCB (center control building). The master clock is generated by a high-quality synthesizer and the trigger clock is generated by counting the master clock. Thus, the frequency of the trigger clock is highly accurate 25 Hz. The signals are distributed from CCB to the all J-PARC accelerator buildings via fan-outs and optical cables; it is a star configuration.

The receiver modules generate trigger pulse, which is defined by a delay from the trigger clock. The delay counter in the receiver module is running at 96 MHz clock, which is generated by using the 12 MHz master clock. The master clock is used as the reference of the system clocks of the digital system, such as the digital LLRF control systems of the synchrotrons. The trigger output jitter the receiver module is less than 1 ns.

There is a concern over stabilities of the power supplies with timing that is not synchronized to the AC line. The power supplies of the J-PARC synchrotrons are switching power supplies, which are not affected by the AC line. On the other hand, the klystron DC power supplies of the linac could get the influence of the AC line. If the amplitude and the phase of the linac RF have variations, the output energy of the linac fluctuates. However, the amplitude and the phase are controlled by the digital feedback system, which aims for the compensation of the voltage sag and the long-



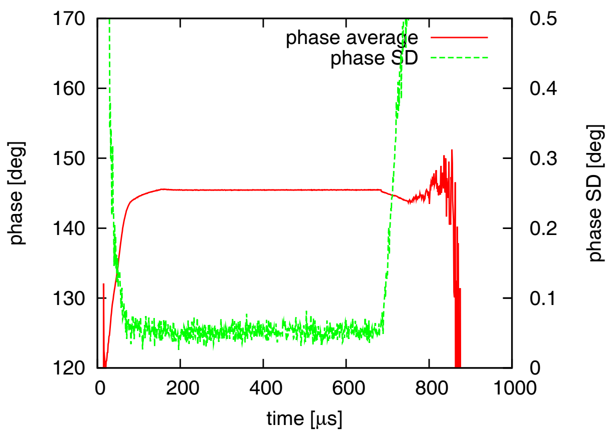


Figure 1: Amplitude and phase variations over 20 RF pulses. Red: average, green: standard deviation.

term drift of the klystron DC power supply. By the feedback system, the amplitude and the phase are controlled in accuracy of $\pm 1\%$ and ± 1 degree, respectively, while the variations in a pulse without the feedback are $\pm 5\%$ and ± 15 degrees, respectively [5]. By the feedback, the cycle-to-cycle variations are also kept small. The typical variations of the amplitude and the phase over 20 RF pulses are shown in Fig. 1. The standard deviations of the amplitude and the phase are less than 2 [Arb. unit] and 0.05 [deg], respectively.

Thanks to the stable linac RF pulses, the variation of the linac beam energy is $\pm 0.01\%$.

Stable RF System

We employ MA-loaded RF cavities to achieve high accelerating voltages [6]. Comparing to the ferrite cavities, the MA cavity can generate twice higher accelerating voltages. Also, the MA cavities has a wide-band frequency response. We choose the Q-value of the cavity as $Q = 2$; no tuning control is necessary to cover the accelerating frequency sweep from 0.938 MHz to 1.67 MHz. The MA cavity can be treated as a passive device and the frequency response is predictable and reproducible. Without the tuning control, the LLRF control system is much more simple than that for the ferrite cavity.

Also, we developed the full-digital LLRF control system based on the DDS (direct digital synthesis) technology [7]. The frequency resolution can be more than 0.1 ppm with the DDS. If the system clock of the DDS is stable, the RF frequency is also very stable and reproducible.

The analog VCO (voltage controlled oscillator), which has frequency accuracies in the order of 10^{-4}, has been widely used in the proton synchrotrons. Because the frequency accuracy is not enough, the radial feedback loop, which controls the RF frequency by referring to the beam position, is necessary to accelerate the protons by using the VCO. The frequency pattern and hence the extracted beam phase (timing) are not very reproducible.

The bending fields of the RCS are very stable and reproducible after warm-ups. By combination of the MA cavity and the digital LLRF based on the DDS, it is possible to accelerate the proton beams without the radial feedback [8]. Therefore the extracted beam timing is very stable.

STABILITY MEASUREMENT

We have performed the preliminary measurement of the beam stability in June 2009. The test setup is illustrated in Fig. 2. The oscilloscope Tektronics DPO70404, which can run at the sampling speed of up to 25 Gs/s, is used for the high resolution timing measurement. The beam current signal in the beam transport from the RCS to the MLF was measured by the current transformer (CT). The scope was triggered by a trigger signal from the J-PARC timing system. Also, the RCS kicker trigger signal, which is generated by the RCS LLRF control system, was taken.

The beam parameters of the stability measurement are listed in Table 2. The beam repetition rate was 25 Hz and both of two RF buckets were filled (two-bunch operation). The beam power delivered to the neutron target was low, 18 kW. We can accelerate low intensity proton beams without activating the phase feedback loop and the RF feedforward for the beam loading compensation. As described in the previous section, the radial loop is not necessary independently of the beam intensity.

The signals taken by the oscilloscope are shown in Fig. 3. In the figure, Ch.2 (blue) is the trigger signal, Ch.1 (yellow) is the beam signal, and Ch.3 (pink) is the kicker trigger signal. The beam signal has two peaks because of the two-bunch operation. We measured the delay from trigger to the first peak. The magnified view of the beam signal (the first peak) with an infinite persistence is also shown in Fig. 4.

The results of the measurement are shown in Table 3. The number of the beam pulses is 1144. Both of the beam and the kicker trigger showed extremely low jitters, in the order of several hundred picoseconds.

Thanks to the stability of the timing system and the RF frequency, no timing variations are observed after the frequency pattern is set during a beam run (a few weeks).

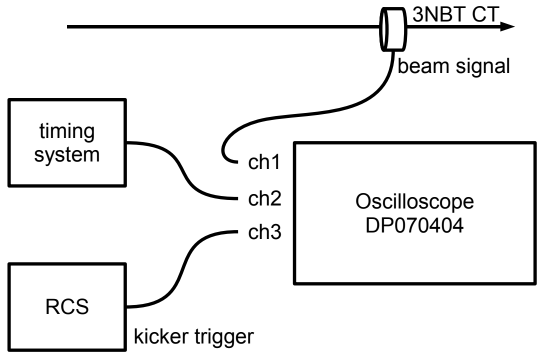


Figure 2: Beam stability measurement setup.

Table 2: Beam Parameters

repetition	25 Hz
macro pulse width	100 μs
linac peak current	5 mA
chopping width	560 ns
number of bunch	2
beam power	18 kW

Thus, the beam stability meets the requirement of both of the Fermi chopper and the MR injection, in the case of the low beam power.

SUMMARY AND OUTLOOK

By employing the non-AC-line-synchronized timing, the MA cavity without the tuning control and the digital LLRF, the timing of extracted beam from the RCS is very stable. The beam jitter is less than 1 ns and the beam timing has no drifts in the low intensity operation.

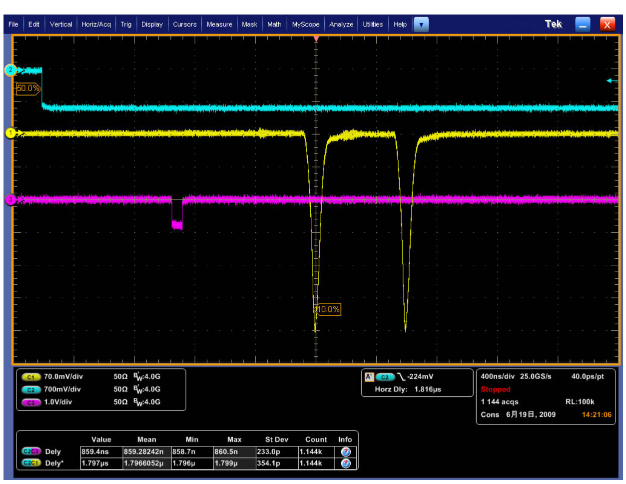


Figure 3: Measured beam signals. Ch.2 (blue): the trigger signal, Ch.1 (yellow): the beam signal, Ch.3 (pink): the kicker trigger signal.

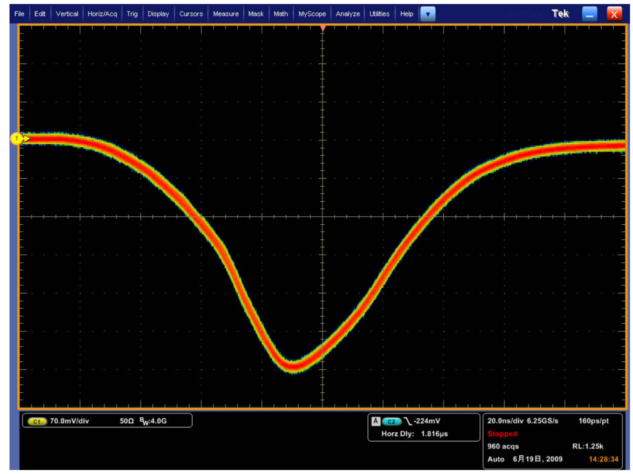


Figure 4: Magnified view of the beam signal (the first peak) with an infinite persistence.

Table 3: Measurement Results of 1144 Beam Pulses

	mean	max	min	St. Dev.
Beam	1.7966 μs	1.796 μs	1.799 μs	354.1 ps
Kicker Trig.	859.28 ns	858.7 ns	860.5 ns	233.0 ps

For the high current, the phase feedback, which modulates the frequency, is necessary to suppress the dipole oscillation due to the beam loading. The beam loading itself changes the phase of the cavity voltage. Hence the extracted beam timing can be changed by the beam loading effects. To reduce the effects, we prepare the beam loading compensation system by using the RF feedforward method. Also, we prepare the beam synchronization system, which measures the beam phase during the acceleration and generate frequency offset pattern so that the extracted beam phase is stable.

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