BUNCH BY BUNCH FEEDBACK SYSTEMS FOR J-PARC MR

M. Tobiyama*, T. Obina, Y. Chin#, Y. Shobuda#, T. Toyama#, M. Tejima# and Y. Kurimoto#
KEK Accerelator Laboratory, 1-1 Oho, Tsukuba 305-0801, Japan
#J-PARC Center KEK and JAEA, Tokai, Ibaraki, Japan

Abstract

Transverse bunch-by-bunch feedback systems for J-PARC MR accelerator has been designed and tested. Bunch positions are detected by Log-ratio position detection systems with center frequency of 12 MHz. The digital filter, which consists of two LLRF4 boards, samples the position signal at the 64th harmonics of the RF frequency. Up to four sets of 16 tap FIR filter with one-turn delay and digital shift gain can be used. Preliminary results of beam test of the system are also shown.

INTRODUCTION

The J-PARC accelerators is composed of a 181 MeV linac, a 3-GeV rapid cycling synchrotron (RCS) and a 50-GeV MR with the circumference of 1.5 km. The RCS provides a proton beam to the Materials and Life science experimental Facility (MLF) to generate intense pulsed neutron and muon beams. A part of the beam extracted from the RCS is injected into the MR, then accelerated up to 30 GeV (phase 1) for high energy physics experiments. The MR has two experimental facilities: one is a neutrino facility which transfers fast extraction beam to the target with pulse solenoid magnet, then convert it to intense muon neutrino beam to inject Super-Kamiokande facility about 295 km away from the accelerator. The other is a hadron beam facility which uses the slow extraction beam. The beam commissioning of the MR has started in May 2008[1]. After overcoming multiple difficulties, the machine has now reached the beam power of more than 100 kW which is about 1/7 of the design power. With the beam, the neutrino experiment (T2K experiment) has already started and has successfully observed the first neutrino event from J-PARC MR.

With the increase of the beam intensity, we have observed a beam loss during acceleration. At the same time, horizontal betatron oscillations have been observed. If the losses are related to the coupled-bunch instabilities, it is necessary to suppress it to reach the design beam power. By theoretical consideration, the instability around the injection energy of will be easily smeared out due to the large nonlinearity coming from the space charge effect[2]. With the acceleration of the beam, the effect reduces with the third power of the gamma factor. The impedance coming from the resistive wall or pulse magnets is estimated to be large enough to cause coupled-bunch instabilities even at the low beam intensities because of the shorter bunch length from RCS and the insufficient shielding effect of the vacuum chamber for lower frequency components.

We have designed the transverse digital bunch-by-bunch feedback systems for J-PARC MR to observe the beam oscillation in transient-domain way, and to suppress the instabilities to help increasing the beam power. Table 1 summarise the main parameter of J-PARC MR.

Table 1: Main Parameter of J-PARC MR

Parameters	Value	unit
Circumference	1567.5	m
Injection Energy	3	GeV
Extraction Energy	30 (50)	GeV
Design power	750	kW
Repetition	0.3	Hz
Injection	0.17	s
Acceleration	1.96	s
slow extraction	0.7	s
RF frequency	1.67 ~ 1.72	MHz
Harmonic number	9	
Number of bunches	6 (8)	
Synchrotron tune	0.0025~0.0001	
Betatron tune (x,y)	22.41, 20.75	

BUNCH FEEDBACK SYSTEM PROTOTYPE

A transverse feedback system consists of mainly three parts, a bunch position detection system, a signal processing part which rejects the unnecessary signal such as DC component or noise, shift the phase of the detected oscillation and to adjust the timing, and a transverse feedback kicker with wideband, high power amplifiers. In this transverse feedback system prototype, we have used the already existing components as much as possible. Figure 1 shows the block diagram of the transverse feedback systems.

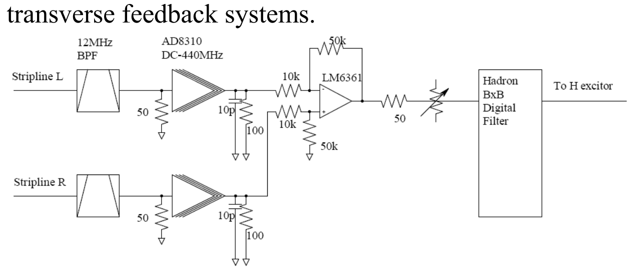

Figure 1: A block diagram of the transverse feedback system prototype installed in J-PARC MR.

As beam signal source we have used a thin and short stripline monitor with length of 18 cm or normal BPM electrode with spiral cut was used[3]. 12 MHz component of the bunch signal, selected by a bandpass filter, was

*makoto.tobiyama@kek.jp

detected by a logarithmic amplifier (AD8310) . The difference signal between the two outputs of the logarithmic amplifiers was calculated with a operational amplifier with gain of 5 to get a bunch position. As a logarithmic amplifier has a huge dynamic range, around 90 dB with AD8310, and the difference output is independent of a beam signal power which increases with the acceleration of the beam, it will help to keep the feedback gain constant during acceleration. Though the response of the logarithmic amplifier, especially in the tail part is fairly slow, it will not harm the system because of far bunch spacing around 0.6 μs. Moreover, the slow response could be regarded as good point for the signal detection with the ADC because the longitudinal bunch position relative to RF signal changes significantly during acceleration. Figure 2 shows an example of the horizontal position signal with the raw beam signal from the stripline exciter. As shown in Fig. 2, the logarithmic amplifier outputs huge random noise without beam signal which is only partially rejected with the digital filter. We plan to add analogue switch synchronized to the accelerator cycle before the ADC to turn off the noise during deceleration and stand-by time. Also it might be better to use the simple subtraction of the signal from normal BPM electrode with spiral cut.

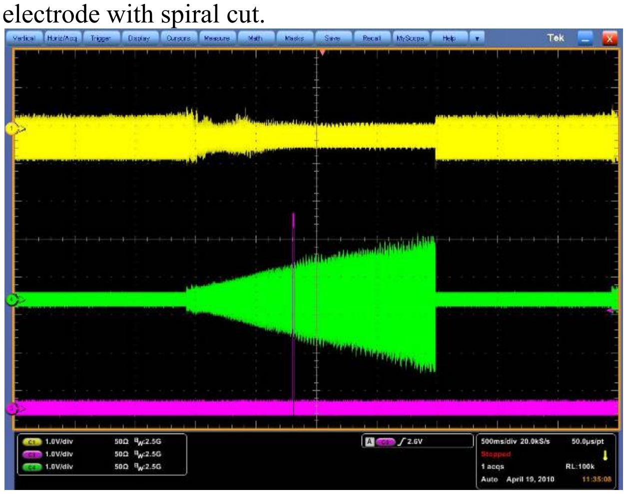

Figure 2: Detected horizontal detection signal using difference of logarithmic amplifiers (upper) and a raw beam signal from stripline exciter (middle).

For the signal processing part, we have selected the LLRF4 boards developed for the prototype system for the digital low level RF processing as the signal processing system[4]. It consists of four 14-bit ADC with maximum sampling speed of 125 MSPS, a Spartan3 FPGA, two 14-bit DAC up to 260 MSPS and a USB interface to communicate with external system. The firmware including EPICS interface and the system integration was made by Dimtel Inc.[5] as shown in Fig. 3.

The clock of the ADC should be synchronized to the ring RF clock. The base RF frequency, around 1.7 MHz, is too low and not convenient to fine control the timing of the input and output of the digital filter. We have decided to use the 64th harmonic of the RF frequency, generated by a PLL, around 108 MHz, as the master clock of the system. The ADC digitizes the beam signal with the clock of around 108 MHz. An adjustable number of samples, from 2 to 64, is then averaged in real time to generate bunch position measurements. External fiducial signal is used to synchronize the timing of the bunches. The system has four sets of FIR filter coefficients with maximum tap number of 16. Appropriate coefficient set can be selected via EPICS or by two-bit hardware control. During the FIR filter process, we can also shift the digital data up to 7 bits to get the higher shift feedback gain. The EDM interface has a built-in filter generator to easily build the filter pattern. The output correction signal is updated at the base RF frequency around 1.7 MHz. The input and output timing can be adjusted with the step of input clock, about 10 ns. We can enable or disable the feedback for each bunch independently. Also, the system has built-in function generator to output sinusoidal or square-wave excitation of given frequency and amplitude. The output pattern (FB ON/OFF, FG ON/OFF) can be also controlled for individual bunches.

The system can acquire up to 2730 turns of bunch-by-bunch data with adjustable trigger delay up to 327 ms. We can also synchronize the data acquisition with the change of the digital filter pattern to make grow-damp experiment of the feedback. The acquired data are transferred to the host for real-time and offline analysis.

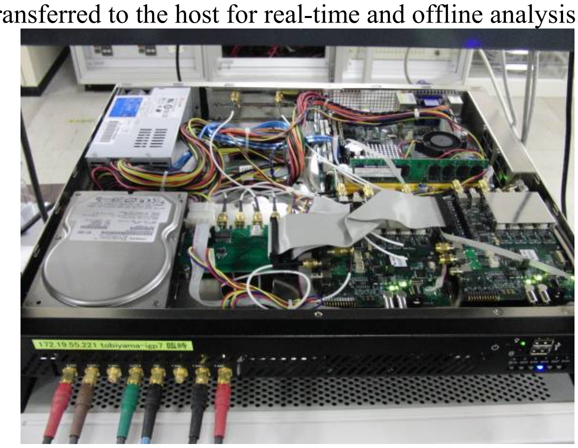

Figure 3: Photo of the digital filter (Dimtel Hadron BxB).

For the feedback kicker, we have used the existing high power amplifiers and betatron tune-measurement exciter striplines[3]. The amplifiers have the bandwidth of 100 kHz up to few MHz with maximum power of 1 kW. Since the low frequency cut-off of the final amplifiers is higher than the lowest betatron frequency, they will need to be exchanged in the near future The stripline kicker has the length of about 1.5 m and the shunt impedance of about 29 kΩ around lowest frequency. We can supply the feedback kick of about 7.6 kV/turn with the maximum differential power.

All the components such as monitor stripline electrode or exciter stripline are placed at the injection straight just below MR-D1 power supply building. Unfortunately, the quality of the timing lines and timing components that distribute the RF signal and fiducial is not good. The measured jitter of the RF timing relative fiducial was about 4 ns peak to peak with almost flat distribution. The created timing clock to digital filter had huge jitter with the same level though the PLL stayed locked, only unlocking during the RF off period. Even though the current high jitter might be acceptable for very slow detection signal from logarithmic amplifiers, we plan to bring a good and precise timing line from the RF station to the feedback systems.

FEEDBACK EXPERIMENT

In this experiment, we have used the horizontal system only under single-bunched operation. At first, we have adjusted the bucket timing (rough) and the ADC timing (fine) by observing the detector signal with one stripline input removed. Figure 4 shows an example of horizontal bunch oscillation of a head bunch in a six bunch train acceleration to neutrino line, recorded with a few ms after injection. By taking an FFT of the data, we have obtained the frequency spectrum with a peak around 79 kHz which is consistent with the horizontal betatron tune of about 23.42.

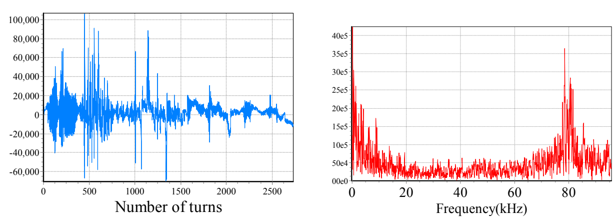

Figure 4: Recorded horizontal bunch oscillation (left) and its FFT (right). The spectrum peak spreads around 79 kHz corresponds to horizontal betatron oscillation tune of 0.42.

By performing the mode analysis of all the bunch data at betatron frequency of 78.4 kHz, we observe highest oscillation amplitudes for modes 0 and -1 (or 9-1=8) as shown in Fig. 5(A). Evolution of the modes with time showed the oscillation has spontaneously damped within 1 ms after oscillation peak as shown in Fig. 5(B). This natural damping of oscillation might be coming from the tune spread due to space charge effect.

The feedback timing was adjusted by observing the relative timing of the bunch signal of exciter electrode and the feedback output passing through the amplifier and the stripline electrode with only one bunch output enabled. We shifted the feedback output timing to center the bunch signal within the feedback kick. We have used both the built-in function generator of the LLRF4 system and the real beam signal with 1-Tap (through) output mode.

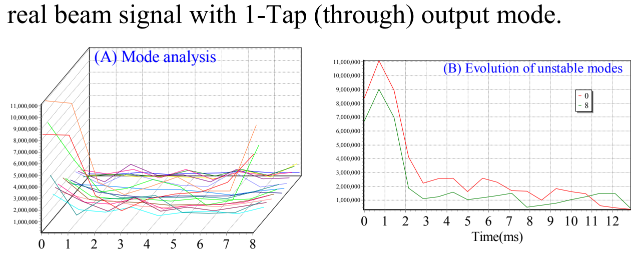

Figure 5: Result of mode analysis (A) and the time evolution (B).

By closing the horizontal feedback loop, we have tried to change the gain and phase of the digital filter and to observe excitation or damping of the oscillation. Under some configuration (possibly positive feedback), the beam was lost soon after injection. Inverting feedback sign showed no beam loss, which means the feedback was negative and stable. By reducing the gain of the feedback, we have seen some growth of the oscillation.

Next, we have tried to reduce the beam intensity greatly to reduce the space charge effect around injection energy and tried to see the growth or damp of the oscillation. With this condition, as it was not easy to see the bunch orbit using the detector made of logarithmic amplifiers, we have used the differential output of a normal BPM electrode by 180-deg hybrid. As the equilibrium phase changes significantly during the acceleration, we have adjusted the timing only around the external trigger timing, that was around injection. By changing the feedback setting from negative to positive, we have observed a slow beam loss which was not observed with the maximum shift gain of negative feedback. Oscillation in the recorded data was not clear and needs to be further investigated.

SUMMARY

We have designed a transverse bunch-by-bunch feedback system for J-PARC MR accelerator using modern digital filter technology. By using the system, we have tried to close the feedback loop. Up to now, it is clear that the feedback system can affect the beam to excite it and introduce loss of the beam. The effect of negative feedback is not clear yet. We will continue the development of the system to achieve good performance to suppress the transverse instabilities and to improve the beam quality.

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