PERFORMANCE OF INJECTION BEAM POSITION MONITORS IN THE J-PARC RCS

N. Hayashi*, P.K. Saha, JAEA/J-PARC, Tokai, Ibaraki, Japan
T. Toyama, KEK/J-PARC, Tsukuba, Ibaraki, Japan

Abstract

It is important to monitor the injected beam trajectory and position into a synchrotron ring. In the J-PARC RCS, there are two specialized beam position monitors (BPM) in the first arc section in order to perform continuous monitoring. They detect the linac RF frequency 324 MHz or its second harmonics, these contributions quickly decrease after a few turns in the ring. Therefore, they are mostly sensitive just injected beam. The RCS adopts the multi-turn injection and painting. These monitors are useful to check the transverse painting process.

INTRODUCTION

The J-PARC (Japan Proton Accelerator Research Complex) is a multi-purpose research center which consists of three accelerators and three experimental facilities [1]. The RCS (Rapid-Cycling Synchrotron) is the second accelerator to provide 1 MW beam power for a Spallation neutron source target, the Material and Life science Facility (MLF), and works as an injection booster for the Main Ring (MR). The RCS has been operated with 181 MeV as the injection energy since 2007 [2]. The injection energy upgrade to originally designed 400 MeV is planed in 2013 to 2014. In this paper, it describes specialized BPM focusing on the injected beam and their application.

The RCS adopts the multi-turn painting injection scheme to reduce space charge effect of the high intensity beam. Here, it describes the transverse painting scheme of the RCS briefly, detail description is given in elsewhere [3]. For vertical painting, two smaller magnets at the L3BT (Linac-to-RCS beam transport line) control vertical angle at the injection point. In case of horizontal painting, it is realized by the dedicated bump magnets in the ring. Two are upstream and other two are downstream of the injection point. These magnets controls time dependent bump orbit during the injection period up to 500 μs.

There are 54 normal BPMs in the ring and their main purpose to measure COD [4]. Since it is sensitive to average charge of the beam, there are two ways to study the injected beam or painting performance using these normal BPM. One is switching the RCS to the "single-pass extraction mode". Another way is a combination of the RCS "DC mode" and "single intermediate pulse injection". Using turn-by-turn measurements mode, the betatron motion is monitoring to know the painting process [5]. These are indirect methods, and they are not consistent with normal user operation.

One may distinguish the just injected beam by detecting the Linac frequency. Using this method, a study at KEK booster detecting the Linac 200 MHz were performed and an outlook for the J-PARC RCS was presented [6]. The Linac RF creates the micro pulse structure whose fundamental frequency is 324 MHz in case of the J-PARC. Due to slippage, this micro pulse structure disappear quickly, after the beam injected into the ring. But it still survives at the first turn. On the other hand, the revolution frequency of the ring, used by normal BPM system (0.469 MHz at 181 MeV injection period), is much lower than that of frequency. This direct method can be applied to a continuous injected beam detection, namely on-line monitoring.

FAST BPM SYSTEM

There are four BPMs which detects Linac frequency around the RCS. Two at the L3BT lines and other two in the first arc section of the ring. Former two are stripline type and determine the injection line orbit into the ring. One is called K-BPM and it is located inside the last L3BT quadrupole magnet. The other is called I-BPM and it is between two injection septum magnets.

The later two in the ring are located at some horizontal dispersion section, about 1 m. The phase space advance between them are about $\pi/2$ with the present tune setting.

The chamber inner diameter is 257 mm and its length is 140 mm. Because available space is quite limited, an electro-static type electrode was employed. They have four electrodes for left, right, up, and down. Its size is 45 mm of length and 49° as an open angle. Typical capacitance for each electrode is about 33 pF.

In order to transport higher frequency, 324 or 648 MHz, low attenuation coaxial cable[1] is used and it is the same as that of the linac BPM. Four cables for each electrode output bring the signal from the main-machine tunnel to the electronics room. Their length are about 60 $\sim$ 70 m. Measured attenuation of the cable is about -5 dB at 324 MHz and -7 dB at 648 MHz, respectively.

Table calibration was performed as same as the normal BPM [4]. A wire which emulates the beam was moved a step of 10 mm pitch over the range of $\pm$60 mm and re-

* naoki.hayashi@j-parc.jp

[1] Andrew HELIAX LDF2RN-50.

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sponse signals of electrodes were taken. A network analyzer was used as both a signal source and a receiver. Two frequency 324 and 648 MHz were used. A position calculation formula is based on that of the linac BPM [7, 8]. The provisional position x and y are calculated as follow.

$$x = \frac{1}{S} \cdot V_{x.diff} \quad (1)$$

$$y = \frac{1}{S} \cdot V_{y.diff} \quad (2)$$

where S is

$$S = \frac{160}{\ln 10} \cdot \frac{\sin(\phi/2)}{\phi} \cdot \frac{1}{r} \quad (3)$$

and $V_{x.diff}$, $V_{y.diff}$ are the difference between left and right or up and down of output of a logarithmic amplifier. Further, the calibration formula of position X and Y are following. There are 15 parameters, a_{ij}, b_{ij}, required for each orientation.

$$\begin{aligned} X &= a_{00} + a_{10}x + a_{20}x^2 + a_{30}x^3 + a_{40}x^4 + a_{01}y \\ &\quad + a_{11}xy + a_{21}x^2y + a_{31}x^3y + a_{02}y^2 + a_{12}xy^2 \\ &\quad + a_{22}x^2y^2 + a_{03}y^3 + a_{13}xy^3 + a_{04}y^4 \end{aligned} \quad (4)$$

$$\begin{aligned} Y &= b_{00} + b_{10}x + b_{20}x^2 + b_{30}x^3 + b_{40}x^4 + b_{01}y \\ &\quad + b_{11}xy + b_{21}x^2y + b_{31}x^3y + b_{02}y^2 + b_{12}xy^2 \\ &\quad + b_{22}x^2y^2 + b_{03}y^3 + b_{13}xy^3 + b_{04}y^4 \end{aligned} \quad (5)$$

A signal process unit is two-width NIM module, which has four inputs and four logarithmic amplifier outputs for every electrode. In addition, two more outputs which are difference between two output channels. Usually they are assigned to difference of Left-Right or Up-Down. There are two versions of units to detect 324 or 648 MHz. Former uses AD8310 and latter uses AD8313 as main log-amp. The output voltage V_{out} in mV is expressed as

$$V_{out} = P \times 200 + bias. \quad (6)$$

Here, P is input signal power in dBm. A bias is 6000 or 10000 and an input range is from 0 to -50 dBm or from -20 to -70 dBm for 324 or 648 MHz, respectively. Two difference signals are read by a fast digitizer and processed on-line position calculation. For study purpose, an oscilloscope was used, particularly to record raw signal (direct from the electrode, not through the log-amp circuit) to assure high frequency bandwidth up to 1 GHz.

EXPERIMENTAL STUDY WITH BEAM

Single-Pass Extraction Mode

This mode is so-called "1/3 mode", because the beam go through only one-third of the ring circumference and directly extracted from the RCS. It is considered as just a beam transport line. Because two BPMs are located at this first arc-section, they can work with this mode. In normal operation, the beam is chopped to make a gap in order to match the ring RF bucket. But with this mode, the chopping can be off, because the beam does not circulate. Difference output signals are plotted as functions of time in Fig. 1. These data are converted to the positions X or Y using the formula (4) or (5). In further, counter plot of X and Y for both BPMs is shown in Fig. 2. Data were taken with various painting conditions, horizontal, vertical or their combinations.

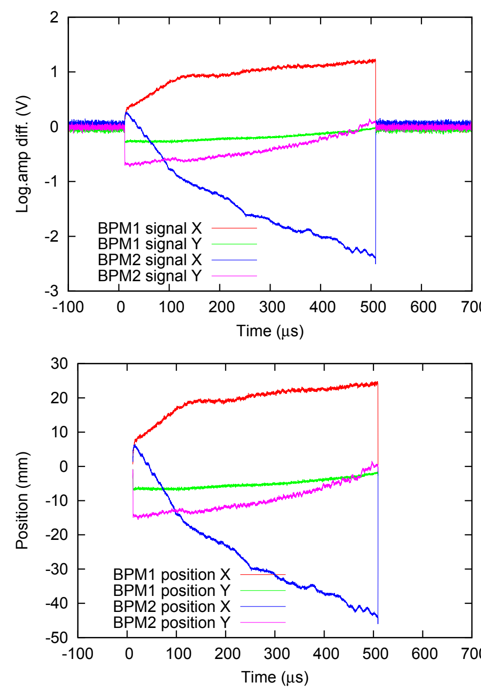

Figure 1: Log-amp difference signal output (upper) and converted position (lower) versus time. The beam was unchopped beam.

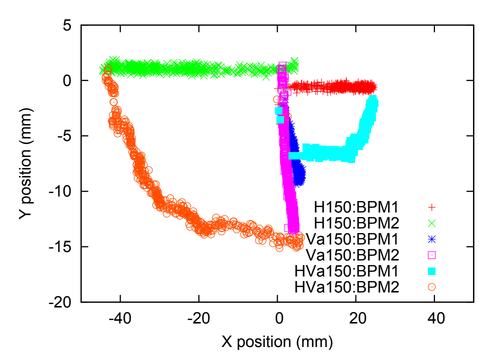

Figure 2: Two BPM X versus Y during 500 μs injection period with various painting conditions. "H150" means only horizontal painting with 150 πmm·mrad emittance.

Since there is two "position" information in the ring, one can reconstruct the injected beam on the phase space. It is also possible to track back by a transfer matrix to the phase space position at the injection point, namely at the charge exchange foil. Since the ring optics are well modeling, the phase space position at the foil (x_0, x'_0), can be expressed

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by two measured position x_1 and x_2 at two BPMs without knowing their slope x_1' or x_2'.

$$\begin{pmatrix} x_0 \\ x_0' \end{pmatrix} = A \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}. \qquad (7)$$

Here, a matrix A can be determined from the model and the effect of dispersion or COD are not included. A reconstructed injected beam footprint is shown in Fig.3. Its beam condition was anti-correlated horizontal and vertical painting with 150 πmm·mrad emittance. On-line painting monitoring is working well with this "1/3 mode".

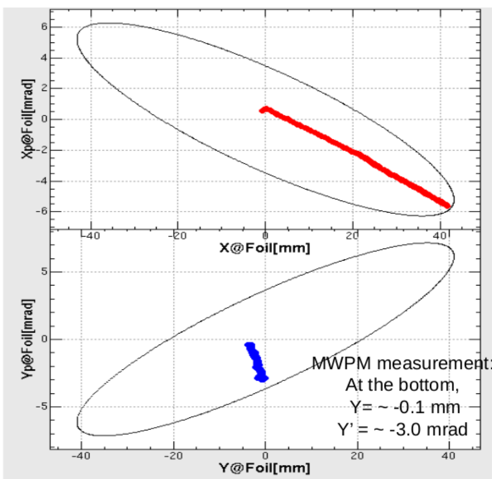

Figure 3: An injection beam footprint on the phase space. It is easy to compare with the desired emittance and painting.

Circulating Mode

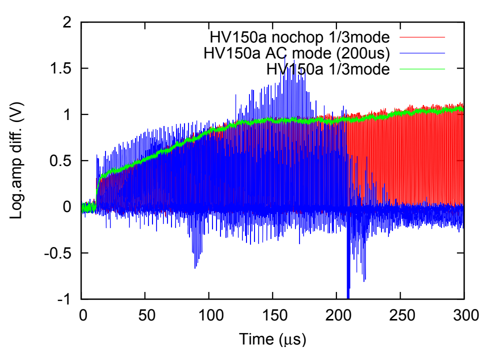

Figure 4: A Log-amp difference output is compared with "1/3 mode" (red: chopped, green: un-chopped, 500 μs injection) and normal circulation mode (blue, 200 μs).

It is interesting to see a comparison with "1/3 mode" and "circulating mode". It is shown in Fig. 4. Thus, the injection period is different, they should be compared up to 200 μs. The signal envelope is somehow similar, but the normal mode seems to have more complex structure. It maybe an interference between the circulating and the just injected beam, or re-bunching.

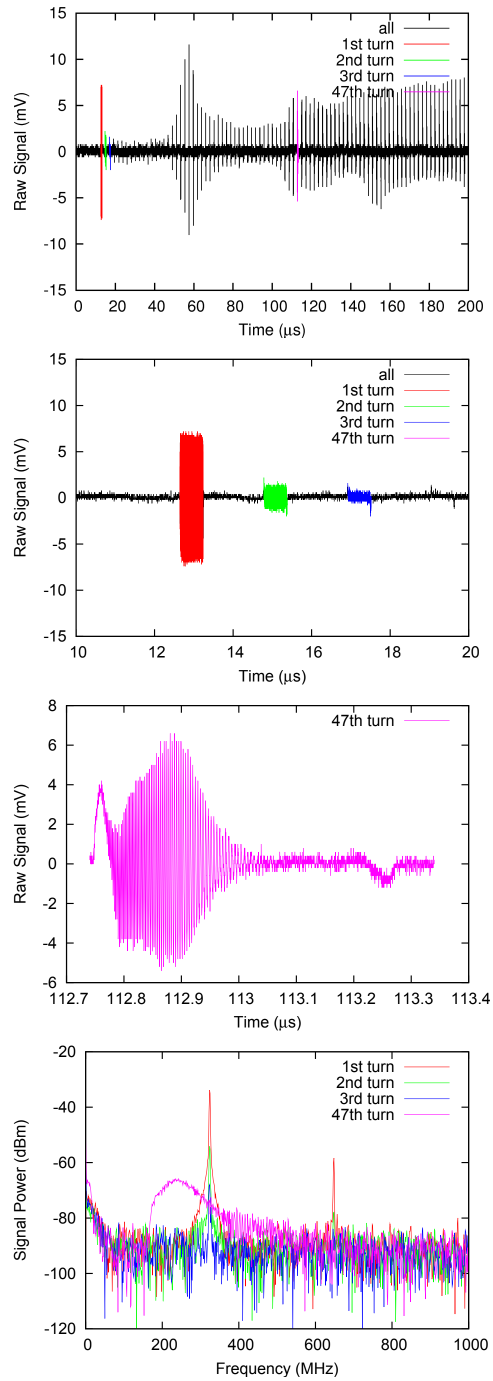

Figure 5: Top is a time domain signal of one intermediate pulse (560 ns). A sampling speed is 5 GS/s. Second and third are its enlargement. The bottom is the FFT spectrum (4096 samples) of specific turn.

Due to a momentum spread $\Delta p/p$, micro pulse time structure dismissed. Naively, time spread ΔT is written as

$$\frac{\Delta T}{T_{rev}} = \eta \frac{\Delta p}{p}. \qquad (8)$$

Here, T_{rev} is the revolution period 2.13 μs, $\eta = \alpha - 1/\gamma$ is a slippage factor -0.69, $\alpha = 1/\gamma_t^2$ is a momentum com-

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paction factor and γ (γ_t) is the Lorentz gamma at 181 MeV (transition energy 9.2 GeV).

This is studied experimentally by observing only one intermediate pulse (one turn) injection. Figure 5 shows the results of time domain and frequency domain of the signal. The Linac frequency (324 MHz peak) disappears after three turns and debunched. After 45th turns (around 100 μs), it indicates the pulse re-bunching. But re-bunched beam spectrum is very broad. A synchrotron frequency is about 3 kHz at injection. Due to the synchrotron motion, the envelope of the signal becomes a peak around 50 μs, but the micro structure re-bunching shows up around 100 μs (Top of Fig. 5). In fact, the timing of intermediate pulse injection is the beginning of 500 μs macro pulse. Re-bunching behavior slightly different, if the intermediate pulse injected in the middle or in the last of the macro pulse time period.

Concerning the position measurement, only the difference of the signal is important, not each absolute signal size. In 2009, it was about $\pm$30 mV and it became smaller about $\pm$8 mV recently. There were two debuncher at the end of linac and the second one was about 165 m upstream of the RCS injection point [9]. The second debuncher was used to control the momentum spread. The designed momentum spread is 0.1 % and it was confirmed by a longitudinal tomography technique [10]. Later some tuning process, it was turned out that different debuncher setting makes lower beam loss at the RCS collimator section and it had been used as a default setting. In fact, it gave larger momentum spread [11]. It seems this is a reason why the high frequency amplitude becomes smaller compared to the previous one. It is also depends on the Linac peak beam current. The raw signal height even gets lower, when the peak current increased from 15 to 25 mA (Fig. 6).

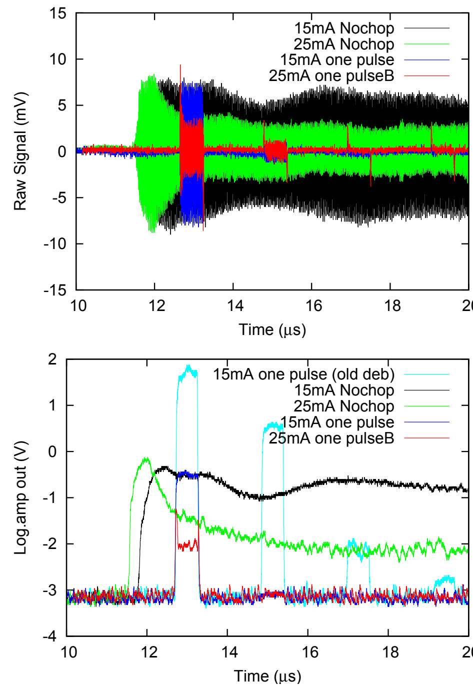

Figure 6: The direct raw signal from the electrode (upper) and 324 MHz Log-amp output (lower) with various Linac beam conditions. Raw data plot of “old debuncher setting” is not shown, but it is about $\pm$30 mV.

SUMMARY

It is presented one pair of high frequency BPM in the RCS. It is very useful for monitoring the painting performance of the just injected beam. It is working very well for “1/3 mode”. However, it seems to be happen, re-bunching process may occur after 100 μs after the injection. Higher frequency components re-appear. It is expected the situation changed after 400 MeV injection. The slippage factor and the revolution period become -0.48 and 1.6 μs, respectively. They may make slower debunching and harder to separate the present turn and the previous turn.

The micro pulse structure at the RCS is very sensitive to various Linac beam conditions, this is certainly affect the signal detection. It is important to do further study in simulation in order to understand the micro pulse dynamics at the beginning of the RCS injection and after in the ring.

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