BEAM POSITION MEASUREMENT DURING MULTI-TURN PAINTING INJECTION AT THE J-PARC RCS

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Abstract

Multi-turn painting injection scheme is important for high intensity proton accelerators. At the J-PARC RCS, a transverse painting scheme was adapted by adding vertical painting magnets to the beam transport line before the injection point, with horizontal painting being performed by a set of dedicated pulse magnets in the ring. To establish a transverse painting condition, it is usual to base on the pulse magnet current pattern. However, it is more desirable to directly measure the beam orbit time variation for evaluation. A linac beam was chopped to match the ring RF bucket. We thought that it would be difficult to measure the position for each pulse; however, the average position could be extracted by introducing a particular device. For the beam injected into the ring, because the linac RF frequency component was diminished due to debunching quickly, one could determine its position in the beginning of the injection period. However, due to rebunching effect the position determination becomes difficult. This problem needs to be resolved.

INTRODUCTION

High-intensity proton accelerators have various applications, such as spallation-neutron production and particle physics experiments. Nowadays, there is an increasing demand for beam powers in the 1-MW range. To realized such a machine with a ring accelerator, multi-turn charge-exchange injection and painting schemes are indispensable key technologies [1]. A painting scheme is necessary to avoid uncontrolled emittance blow-up and reduce beam loss. In such a scheme, the injected beam is steered at every turn to obtain the desired particle distribution in phase space. There are two kinds of painting: transverse and longitudinal. Herein, only transverse painting is discussed.

The Japan Proton Accelerator Research Complex (J-PARC) has three accelerators and three experimental facilities [2]. H^- beams accelerated by a linac are injected into a rapid-cycling synchrotron (RCS) with a repetition rate of 25 Hz. The injection energy used to be 181 MeV; however, it was upgraded to 400 MeV for decreasing the space charge effect. The front-end intensity was also upgraded for the 50-mA operation. The RCS provides beams to downstream experimental facilities, the Materials and Life Science Experimental facility (MLF), Neutrino Experimental Facility (NU), and Hadron Experimental Facility (HD). The latter two facilities are after the Main Ring (MR). Macro pulses are a type of pulse injected into the RCS and have a pulse length of up to 500 μs. The beam is chopped to match the RCS RF bucket, and each chopped bunch is called an "intermediate bunch." The beam in the linac has a micro bunch structure of 324 MHz.

Several procedures were devised to set up suitable painting conditions.The multi-wire profile monitor is accurate in space but not in time, and it cannot be used when the RCS is the beam circulation mode. Thus, the RCS was set to the injection dump mode or single-pass extraction mode. In the latter mode, the beam travels only one third of the ring circumference before being extracted to the downstream beam transfer line (1/3 mode). To establish a fixed injection orbit, the current pattern of the pulsed magnets were set to trapezoidal mode [3]. Only one intermediate pulse was used along with a turn-by-turn BPM function to get the injected beam point in phase space. With varying pulse magnet timing with respect to the injected beam, one could reconstruct phase space footprint of painting injection [4]. In the "1/3 mode", unchopped beams can be transferred though the RCS. The dedicated BPM waveform data were stored by an oscilloscope and analyzed offline [5]. In this research, we analyzed the changes in beam position over the whole injection period for normal operation and these changes were compared with data of special beam conditions.

INJECTION SYSTEM AND BPM

Horizontal painting was implemented using four pulsed magnets, of which two were installed upstream and the other two were installed downstream of the injection point, where a charge-exchange foil was placed. As the horizontal position of the injection beam is fixed, the already circulating beam was continously adjusted during the injection period such that the injected beam was added to the outer part of the intended horizontal ellipse in phase space. For vertical painting, two dedicated pulsed magnets on the Linac-to-3 GeV RCS beam transport line (L3BT) were used. They controlled the vertical slope of the beam orbit at the injection point. In fact, painting can begin either from the center or the edge of the ellipse. Horizontal painting always begins from the center to the edge because it is advantageous to reduce the number of foil hits, thereby reducing the beam loss. However, for vertical painting, one can choose either alternative. If the vertical painting direction is the same as the horizontal painting direction, it is referred to as "correlated painting," however, if it is opposite, it is referred to as "anti-correlated painting." There is debate as to which one is more advantageous [6].

There are two strip-line type BPMs, "K-BPM" and "I-BPM" having internal diameters of 180 and 240 mm, respectively, on the L3BT after the two vertical painting magnets. Another pair of BPMs (BPM324) is installed in the ring at the first arc-section (Cells 06 and 07) before the extraction

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point to measure the linac micro bunch frequency. They are of the electrostatic type, and their internal diameter is 257 mm. They are designed to transfer high-frequency signals and are different from other BPMs [7].

The present linac BPM electronics serves only a limited function. The signal from the BPM is connected to a log amp circuit, which detects 324-MHz components and outputs the difference between the signal from the two opposite electrodes. The beam synchronous trigger activates 5 μs before the end of the beam, and a digitizer displays the last part of the macro pulse. One of these intermediate pulses and its time window are selected manually and the pulse position is calculated. Not all macro pulses can be digitized and processed because the network load would be considerably heavy. In the case of an unchopped beam, one could calculate the beam position for every time step. It is possible to automatically perform this procedure in principle.

Libera Single Pass H is a BPM signal processor developed for hadron linacs [8]. Its ADC sampling rate is only 125 MHz; however, using undersampling technique, it can detect the fundamental or second harmonic amplitude and calculate the beam position. This was mainly used for performing the following measurements. Currently, the ADC sampling rate is 119 MHz and the decimation is 119. Furthermore, one measured point corresponds to one micro second. Some time windows have more or less bunches, and this amplitude variation occurs for all four electrodes. However, only their relative strength is necessary for position calculation. Thus, continuous beam position measurements can be performed even for chopped beams.

ANALYSIS

The micro bunch structure disappeared after injection, and smeared out within a few turns. This feature is used for distinguishing the injected beam from the circulating beam [9]. However, the micro bunch structure actually reappeared after several tens or even a hundred micro seconds. This rebunching process needs to be understood. When the ring RF was off, rebunching phenomena were not detected. As the Linac beam peak current is constant at 40 mA, the desired beam power for each experimental facility is adjusted by changing the number of bunches in the RCS, changing the macro pulse length, thinning the intermediate pulses, or changing the chopped width. Recent typical beam parameters are as follows. For the MLF, they are one bunch, 225μs, 32/32, and 418 ns. For the NU, they are two bunches, 500μs, 28/32, and 470 ns. The painting area was also different for each facility: 200π mm·mrad and anti-correlated for the MLF and 50π mm·mrad and correlated for the NU.

Plots of typical beam position over time for K-BPM in both the MLF and NU modes are shown in Fig. 1. It is evident from the figure that the vertical position varies over time. For the NU mode, there are clear and systematic position dips. As discussed above, there are missing intermediate pulses

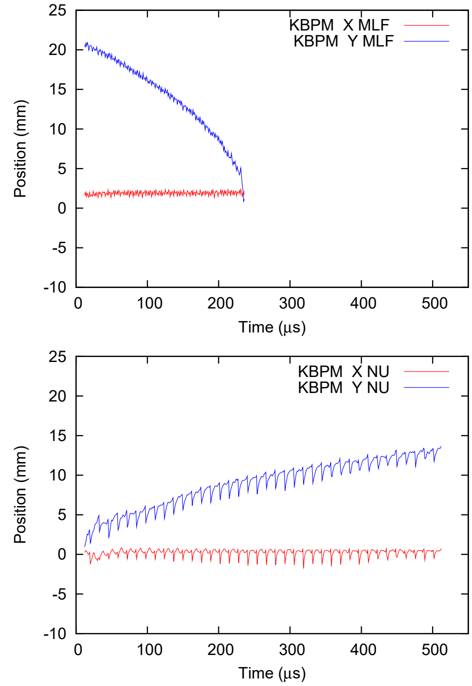

Figure 1: Plots of beam position vs. time for K-BPM. Positions for both the MLF and the NU modes are shown.

due to thinning, and the feedforward works inappropriately for these missing pulses.

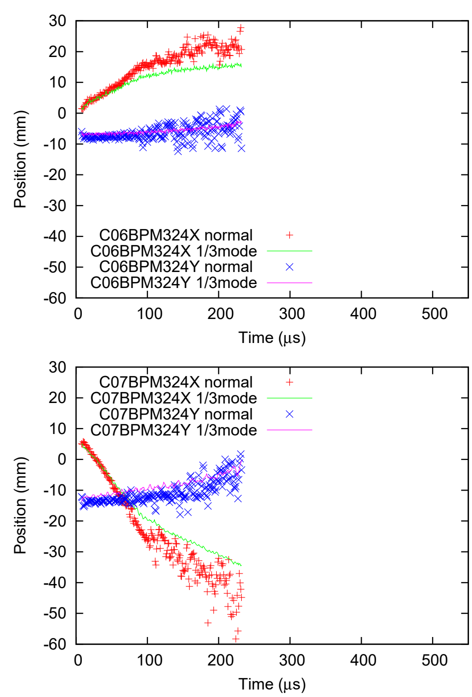

Figure 2: Data of Cell 06 and 07 BPM324 for MLF mode. Both normal operation and 1/3 mode data are shown.

Beam position data for the ring BPMs are shown in Fig. 2. Both normal and 1/3 mode data are plotted in each figure. At the beginning, the position variation is the same for both

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modes; however, after 60 ∼ 70μs, the position differences between the normal and 1/3 modes become larger.

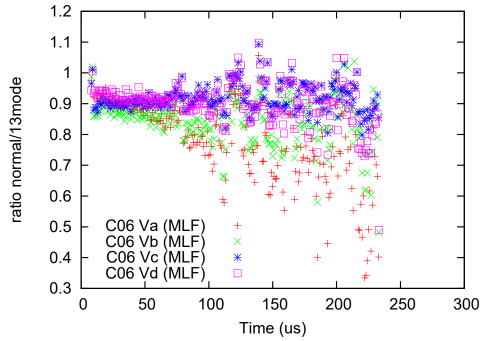

Figure 3: Cell 6, 7 BPM324 voltage amplitude ratio between normal operation and 1/3 mode for the MLF beam.

Voltage amplitude ratios of the normal operation mode to the 1/3 mode are plotted for all four electrodes in Fig. 3. The previously injected beam still has some 324-MHz components but not in phase, which is why the ratio is slightly smaller than one, even in the beginning, except for the first turn. This appears to be a multi-turn effect.

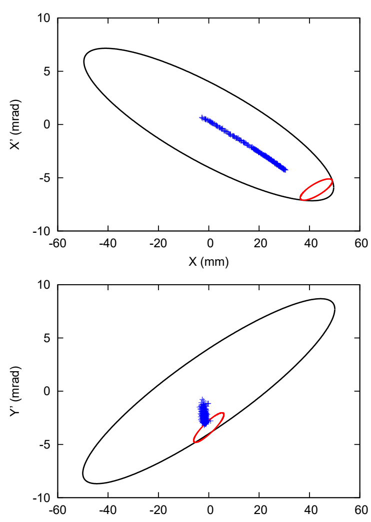

Figure 4: The reconstructed injection beam position in phase space for the 1/3 mode.

Using the data from these two BPMs, the beam position in phase space can be reconstructed. In addition, it can be traced back to the injection point using a transfer matrix. The position of the injected beam in phase space for the 1/3 mode is shown in Fig. 4. A similar plot for the normal operation mode is shown in Fig. 5. The difference between them is believed to be an effect of rebunching.

CONCLUSIONS

The new hardware allowed us to measure the single-pass beam position for the entire macro pulse length, even in the chopped mode. Using this device, we showed that the linac

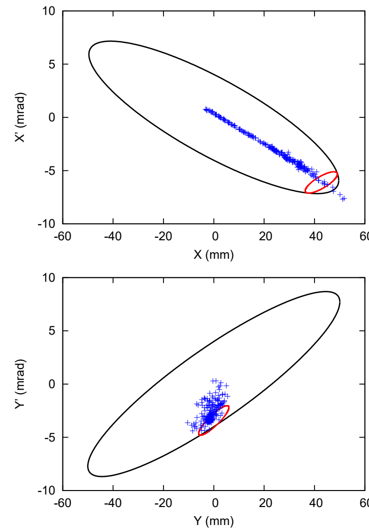

Figure 5: Phase space tracking for normal operation.

feedforward control has problems with the beam thinning. The vertical painting process was directly observed by the BPMs on the L3BT. Results for the anti-correlated MLF mode, correlated MR mode, and different painting sizes were also presented. Both the horizontal and vertical painting processes were also observed for the 1/3 mode using two BPMs in the ring. In addition, we attempted to directly observed the painting behavior for the normal operation. For the first few tens of micro seconds, the painting behavior was similar to that of 1/3 mode; however, the rebunching phenomena subsequently influenced the measurements. So far, we have only focused on the fundamental frequency. Rebunching phenomena might be different for second harmonics and should be studied. There are two debunchers after the last linac acceleration cavities. In particular, the second debuncher changes the momentum spread and may have an affect on debunching or rebunching in the ring. The detailed mechanism of rebunching is itself an interesting subject to study [10].

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