Energy measurement and correction for stable operation in J-PARC

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Abstract. In Japan Proton Accelerator Research Complex (J-PARC), the beam accelerated up to 400MeV in the Linac is injected to 3 GeV rapid cycling synchrotron (RCS), and we realize the high intensity beam by using multi-turn injection. During a user operation, we rarely detected the beam loss at the high dispersion area in the RCS or the beam collimator section in the extraction beam transport line. These incidents indicate that the beam loss is caused by the momentum shift of RCS injection beam according to the experimental and simulated data. In the beam commissioning, we check the Linac beam momentum just before a user operation of the RCS. However, we could not previously measure the Linac beam momentum during the user operation because we adopt the multi-turn injection with synchrotron oscillation for longitudinal plane. Therefore, we measured the beam momentum in the beam injection line of the RCS. Because the Linac-to-3-GeV-RCS Beam Transport line (L3BT) has the high dispersion areas, we estimated the RCS-injection momentum from the beam orbit data by the Beam Position Monitors (BPMs). We measured the beam position data by these BPMs, and estimated the momentum shift by using the data and beam simulation. As a result, we found the momentum fluctuation during the user operation, and the fluctuation $\Delta p/p$ was shifted up to 0.1% from the reference. In addition, to suppress this beam loss induced by the momentum fluctuation and shift, we developed the momentum correction system. The fluctuation was achieved less than $\pm 0.02 \%$ with this system. Finally, the beam loss incidents induced by the beam momentum shift does not occur, and we successfully achieved the more stable user operation in J-PARC.

1. INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose proton accelerator facility such as experiments of particle physics, nuclear physics, materials science, and life science. The J-PARC facility composes of three accelerators, which are a 400-MeV Linac, a 3-GeV rapid cycling synchrotron (RCS), and a 50-GeV main ring synchrotron (MR), and three experimental facilities, which are a materials and life science experimental facility (MLF), a hadron experimental hall, and a neutrino beam line to Kamioka [1].

In the J-PARC Linac, a negative hydrogen ion beam is accelerated up to 400MeV and is injected into the RCS. Then, negative hydrogen ions are exchanged to protons using a carbon foil located at the RCS injection point. During the injection, a transverse injection painting is utilized to manipulate the transverse beam profile according to the requirements from the experimental facilities as well as to mitigate the space-charge induced beam loss in the RCS and decrease the foil hitting rate of the
The injected beam is accelerated up to 3 GeV at the RCS and is delivered to MLF and MR. Figure 1 shows the multi-turn injection scheme in the longitudinal phase space. To realize the longitudinal injection painting, we use momentum offset injection and the rf bucket in combination with superposing a second harmonic rf voltage [4]. The momentum corresponds to the beam energy. Typically, the momentum offset value is $\Delta p/p = -0.20\%$ in order to mitigate the space charge effect.

During a user operation of the RCS, we rarely detected the beam loss at the high dispersion area in the RCS or the beam collimator section in the extraction beam transport line to the MR (3-50BT). According to the experimental and simulated data, these incidents indicate that the beam loss is caused by the momentum shift of injection beam. If the beam having the momentum lower than set value is injected from Linac to RCS, we can realize the beam with reduced the space charge force because the longitudinal beam density decreases. However, the beam loss occurs at high dispersion area in the RCS because the momentum spread is too large. On the other hands, if the beam having the momentum higher than set value is injected to the RCS, we cannot realize the beam with reduced space charge force because the density is higher than the required one. As a result, beam halo is generated in the transverse direction, and the beam loss occurs at the collimator-section in the 3-50BT. Namely, the beam loss occurs when the beam injected from Linac to RCS has the undesired momentum.

We experimentally confirmed these predictions. We used the most downstream rf cavity in a Linac-to-3-GeV-RCS Beam Transport line (L3BT) to inject the beam with changed momentum into the RCS. When the momentum lower than set value was injected to the RCS, the beam loss increased at high dispersion area in the RCS. When the momentum higher than set one was injected, the beam loss increased at the collimator section in the 3-50BT. These results were correspondent with our expectations. According to a request of the RCS, the momentum shift has to be within $\pm0.05\%$.

In the Linac and L3BT, we use the time-of-flight (TOF) to measure the momentum, but the precision is about $\pm0.1\%$. On the other hand, an RCS’s monitor precision is about $\pm0.001\%$. Therefore, in the beam commissioning, the Linac beam momentum is checked using the RCS’s monitor under special beam condition without longitudinal injection painting just before a user operation. However, we could not previously measure the momentum during the user operation, because we adopt the multi-turn injection with synchrotron oscillation for longitudinal plane. To measure the momentum during the user operation, we have to adopt new momentum measurement method in the Linac or L3BT, and the precision has to be more accurate than the RCS request ($\pm0.05\%$).

The multturn injection painting is key technique to realize the high intensity accelerator such as J-PARC accelerator. We must measure and correct the beam momentum injected into the RCS to realize the stable user operation in J-PARC.

2. MOMENTUM MEASUREMENT

2.1. Dispersion Function and BPM Locations
The L3BT has 8 bending magnets, and there is high dispersion area. Figure 2 shows the L3BT until the injection point of the RCS. Black line, circles, and squares indicate dispersion functions in the horizontal direction, BPM locations, and rf cavity locations, respectively. There are 2 cavities (debunchers) in the L3BT, and we fine-tune a longitudinal-beam’s momentum and spread using these cavities. The dispersion function has a maximum value of about 3 m downstream the L3BT. Hereinafter, this area is called “high dispersion area”. The beam momentum is constant because there is not a rf cavity in high dispersion area. This section addresses new centroid-momentum measurement method using 10 BPMs in high dispersion area.

2.2. Analysis Methods
As described above, the beam momentum is checked when the beam is injected from Linac to RCS under the special beam condition just before the user operation. We define this orbit as reference orbit ($D_p/p = 0.0 \%$). We compare the reference orbit with the current orbit measured during user operation, and acquire the beam centroid momentum. This difference orbit between reference and current orbits is analogous to dispersion function, and the factor means the momentum.
commissioning, respectively. In 3rd figure, red points show the difference orbit obtained by subtracting reference orbit from current one. Finally, the momentum shift can be obtained when dividing this difference orbit by the dispersion function.

Not to get the incorrect value, this system adopts two methods. First, horizontal beam positions are measured with 10 BPMs. Second, we compare the measurement data with the simulation data using Strategic Accelerator Design (SAD) developed in KEK [5] (see purple line in 3rd figure from top of Fig. 3). The 4th figure shows the difference between measurement and simulation data. When this difference is sufficiently small, we judge that the measurements are correct finally. Namely, we can get the pure orbit shift induced by the momentum shift, because the locations where each BPM is installed have different dispersion functions. In case of the Fig. 3, the momentum shift was 0.054 %. When the momentum was measured just before the user operation, the measurement value using BPMs in the L3BT was coincident with the one using the RCS monitor, and the precision is the almost same as the one of RCS monitor (about ±0.001 %).

3. MOMENTUM CORRECTION SYSTEM

We want to decrease the momentum fluctuation within ±0.05 % because we adopt the momentum offset injection in the J-PARC RCS. The momentum fluctuation attempts to be corrected within ±0.02 % to realize the ideal multiturn injection in the longitudinal phase space.

There is nothing except a RF cavity to adjust the beam momentum. Ideally, it is desirable to suppress the momentum fluctuation with debuncher 1 and 2. For that purpose, we have to measure the momentum immediately after debuncher 1 and 2, respectively. However, it is difficult to measure the momentum between debuncher 1 and 2 because dispersion value is small ($h = 0.7$ m). Therefore, we attempt the momentum correction using the debuncher 2 only because this is the cavity just before RCS injection (see Fig. 2).

In general, the amplitude and phase are changed to adjust the momentum. However, the multipactoring may occur in the debuncher when the amplitude is changed in the user operation. Not to damage the cavity by the multipactoring, the phase is shifted only. In addition, we confine the phase shift range up to ±30 degrees to guarantee the longitudinal beam quality. If phase is changed out of ±30 degrees, the gradient of Electric field is small, and the momentum spread is smaller than design value. Under these conditions, the corrected value is simulated using SAD. If -6.6 degrees is added into the current phase in the debuncher 2 to decrease the momentum in Fig. 3, the momentum value is close to zero.

The momentum is measured with the BPMs in the L3BT regardless of each destination (MLF or MR). To observe the momentum in the MLF destination only, we adopt the moving median filter for the following reasons.

1) Deriver more beam to the MLF than to the MR.
2) The momentum changes slowly over several days.

Moreover, the correction is performed only when the threshold value is continuously exceeded.

Figure 4: Momentum trend from 12th April 2018 to 1st July 2018.
Figure 4 shows the momentum’s long-term trend from 12th April 2018 to 1st July 2018. Red line shows the momentum injected to the RCS. Black line shows the momentum prediction without the momentum correction system. If the correction system did not work, the momentum would have been off by 0.1 %. The fluctuation was achieved less than almost ±0.02 % with this system. Note that, some momentum values exceed out of ±0.02 %. There are two reasons. First, when the threshold value is exceeded one time only, the momentum value is recorded but the correction is not performed. Second, the same thing happens when the momentum is intentionally changed for beam study. From the above, we were successful in the suppression of momentum fluctuation during the user operation. This correction value (±0.02 %) satisfies the request in the RCS (within ±0.05 %). In addition, the beam loss induced by the momentum shift did not occur at the high dispersion area in the RCS and the collimator section in the 3-50BT, and we successfully achieved the more stable user operation in J-PARC.

3.1. Future Policies
The rf amplitude of debuncher 2 is smaller than another rf cavities because the debuncher is a device to slightly enlarge the momentum spread. If the momentum fluctuation is out of ±0.06 %, We cannot guarantee the longitudinal beam quality with the debuncher 2 only. To guarantee the quality whatever the momentum is shifted further, we are developing the momentum correction system using debuncher 1 and 2. In addition, we are investigating the cause of momentum fluctuation.

4. CONCLUSION
The beam momentum injected to the J-PARC RCS had not been measured during the user operation until now. According to a request of the RCS, the momentum has to be within ±0.05 %. We measured the momentum using BPMs in the L3BT between Linac and RCS, and found the momentum fluctuation. To suppress the fluctuation, we developed the momentum correction system using one rf cavity. As a result, the momentum fluctuation was achieved less than ±0.02 % with this system, and we are supplying the more stable beam to the J-PARC users. We are developing the momentum correction system using two rf cavities to guarantee the longitudinal beam quality whatever the momentum is shifted further.

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