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# Dependence of charge-exchange efficiency on cooling water temperature of a beam transport line

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## Abstract

The 3-GeV Rapid Cycling Synchrotron at the Japan Proton Accelerator Research Complex supplies a high-intensity proton beam for neutron experiments and to the Main Ring synchrotron. Various parameters are monitored to achieve a stable operation, and it was found that the oscillations of the charge-exchange efficiency and cooling water temperature were synchronized. We evaluated the orbit fluctuations at the injection point using a beam current of the injection dump, which is proportional to the number of particles that miss the foil and fail in the charge exchange, and profile of the injection beam. The total width of the fluctuations was approximately 0.072 mm. This value is negligible from the user operation viewpoint as our existing beam position monitors cannot detect such a small signal deviation. This displacement corresponds to a $1.63 \times 10^{-5}$ variation in the dipole magnetic field. Conversely, the magnetic field variation in the L3BT dipole magnet, which was estimated by the temperature change directly, is $4.08 \times 10^{-5}$. This result suggested that the change in the cooling water temperature is one of the major causes of the efficiency fluctuation.

**Keywords:** J-PARC, Proton synchrotron, Injection, Orbit, Charge exchange, Stability, RCS, Temperature

## Introduction

The 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) was constructed to supply a 1-MW, high-power proton beam to the Main Ring (MR) synchrotron and Material and Life science experimental Facility (MLF) [1]. The RCS accelerates the proton energy from 400 MeV to 3 GeV at a repetition rate of 25 Hz. While operating such a high-intensity hadron accelerator, the most important aspect is the reduction of the beam loss around the accelerator to maintain a hands-on maintenance condition. A major cause for the beam loss is a halo, generated by the nonlinearity of the space charge force. To mitigate this space charge effect, the RCS adopts a painting injection scheme for the injection process in the transverse and longitudinal phase spaces [2]. In the injection beam-painting process, to achieve an arbitrary distribution in the transverse phase space, the injection beam orbit must be shifted with respect to the circulating one. To realize this beam-injection scheme, it is necessary to superimpose the injection beam on the circulating beam in the phase space. However, according to Liouville's theorem [3], this is impossible when the charge and polarity of the injection and circulating beams are same. Therefore, we accelerate a negative hydrogen ($H^-$) ion beam using a linac and place a charge-exchange foil at the injection point of the RCS. Owing to the interaction between the $H^-$ beam and foil during the ion passage through the foil, two electrons are stripped and the $H^-$ ion is converted into a proton. This process enables the overlapping of the injection beam with the circulating beam.

Electron stripping from the $H^-$ ion by the foil interaction is a stochastic phenomenon, and a certain number of $H^-$ and neutral hydrogen atoms ($H^0$) exist without the charge exchange. Further, when the injection beam profile is large and its tail protrudes from the edge of the charge-exchange foil, the tail also misses the foil and $H^-$ ions remain. These $H^-$ and $H^0$ particles will be lost around the injection area if they are not removed. Therefore, we installed additional foils to lead these particles to the injection dump [4]. Figure 1 shows the injection scheme of the RCS. In principle, the charge-exchange efficiency of the foil is a function of the material and density of the foil [5]; in reality, the efficiency also depends on the injection beam shape, foil shape, existence of a pinhole, deformation of the foil, and other factors. Contrarily, the injection dump has a capacity of 4 kW for radiation and heat treatments [6]. This value corresponds to 3% of the injection beam at 1-MW acceleration. The number of particles in the injection dump are constantly monitored by a current transformer (CT), so as not to exceed its capacity [7]. Typically, the charge-exchange efficiency of the foil itself is approximately 99.7%, and the amount of the tail that misses the foil is approximately 0.2%. Therefore, approximately 99.5% of the injection beam can be accumulated in the RCS in an ordinal operation. The upper graph of Fig. 2(a) shows a time history of the CT signal. The raw signal was fast Fourier transform (FFT)-processed to improve its signal-to-noise ratio. In this case, we delivered $4 \times 10^{13}$ protons per pulse (ppp) to the MLF (number of protons in this operation corresponds to the 500-kW output power in the RCS) and $5 \times 10^{13}$ ppp to the MR (this value corresponds to the 500-kW output power in MR) at a repetition rate of 25 Hz [8]. In the Fig. 2, we can observe crests and troughs in a cycle of several minutes, implying that the charge-exchange efficiency oscillated. Therefore, we investigated the cause(s) of these fluctuations.

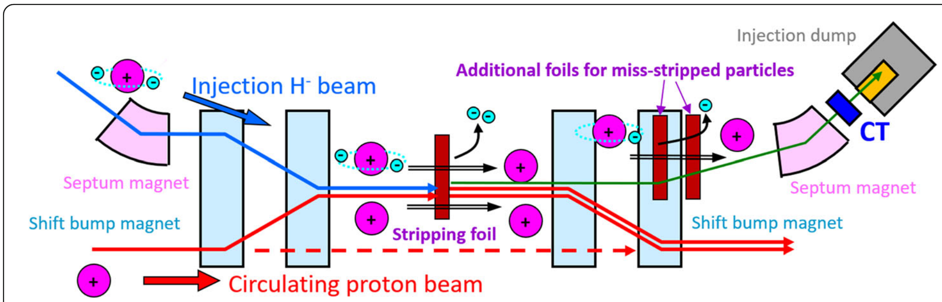


**Fig. 1** Injection scheme of RCS

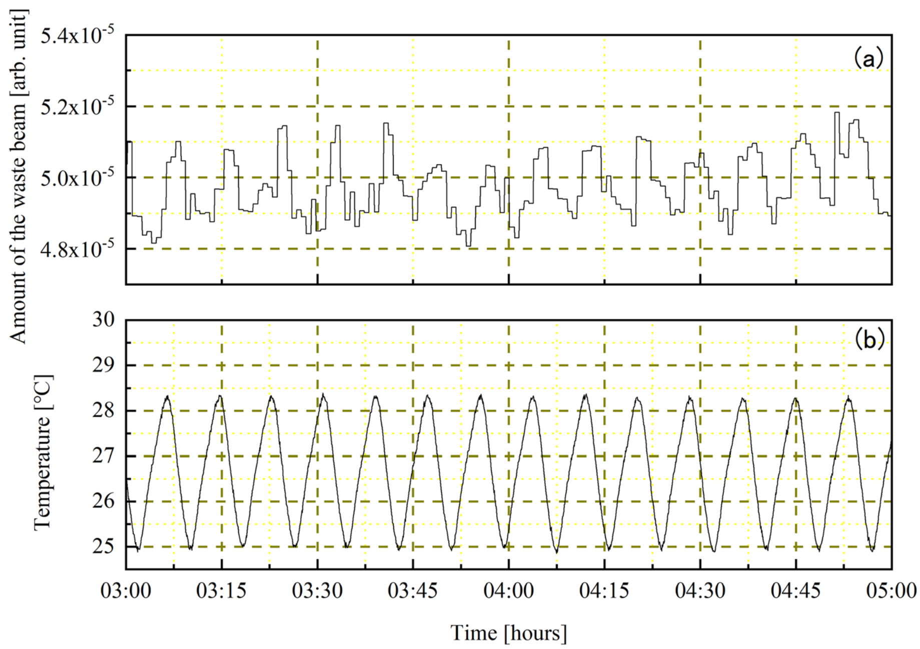


**Fig. 2** Trend of the FFT signal of (**a**) injection dump CT and (**b**) cooling water temperature. This data was obtained during the user operation on 10th Dec. 2018

## Methods

### Correlation between charge-exchange efficiency and cooling water temperature

In the RCS, to monitor the status of each device and beam condition during the continuous operation, we simultaneously measure various parameters and compare their trends [9]. On investigating the trends of the graphs, a correlation was found between the oscillations of the magnet cooling water temperature in the RCS tunnel and crests and troughs of the CT signal (Fig. 2). This cooling water temperature is controlled within the range of 26.7 °C ± 1.7 °C. After a certain period passed since the start of the operation, the temperature of each magnet stabilizes, and the temperature of the cooling water oscillates in the range of 25.0 °C–28.4 °C. Figure 2 shows that the frequency of the CT signal fluctuations is completely synchronized with that of the temperature oscillations. In contrast, the timing of the peaks is shifted. This is due to the time difference of the temperature changes in the magnet and cooling water. The temperature changes in the magnet coil and core exhibit a delay compared to those in the cooling water.

Thus, we considered the effect of the change in the magnet temperature on the charge-exchange efficiency. It can be assumed that the fluctuations in the charge-exchange efficiency were caused by the change in the injection beam parameters. The beam transport line from the linac to the 3 GeV RCS (linac 3-GeV RCS beam transport line, L3BT) is separated by the tunnel wall between the linac and RCS accelerator tunnel. Only the temperatures of the L3BT magnets located in the RCS tunnel are controlled by the cooling water of the RCS. The cooling water temperature in the linac tunnel is precisely controlled to keep the temperature fluctuations below ±0.1 °C, to maintain the resonance condition of the linac RF cavity. Therefore, we can neglect the influence of the linac side. Figure 3 shows the layout of the magnets of the L3BT line and RCS.

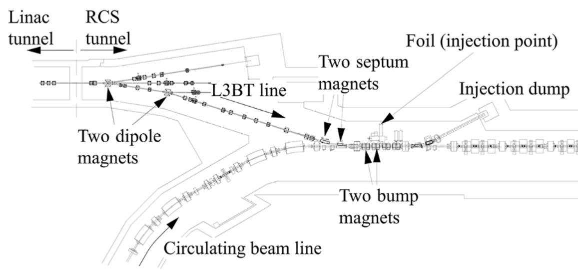


**Fig. 3** Layout of L3BT line and RCS

Here, we assumed that the influence of the temperature change is small, and only the bending angle of the dipole magnet was affected. Under this assumption, the change in the charge-exchange efficiency is considered because of the change in the position of the injection beam with respect to the foil. A change in the injection beam position causes a change in the amount of the tail that misses the foil and fails in the charge exchange. As the number of particles that actually fluctuate are evaluated based on the deviation of the charge-exchange efficiency, we can convert it into the variation of the injection beam position using the injection beam profile. In the L3BT line, there are no vertical dipoles except the vertical correction magnets. Therefore, we need to consider only the movement in the horizontal plane.

Furthermore, we evaluated the influence of the cooling water temperature on the magnets. The relation between the injection beam profile and foil position is shown in Fig. 4.

The temperature fluctuations induce a change in the height of the magnet gap, which results a change in the magnetic field strength of the L3BT dipole magnets and shift of

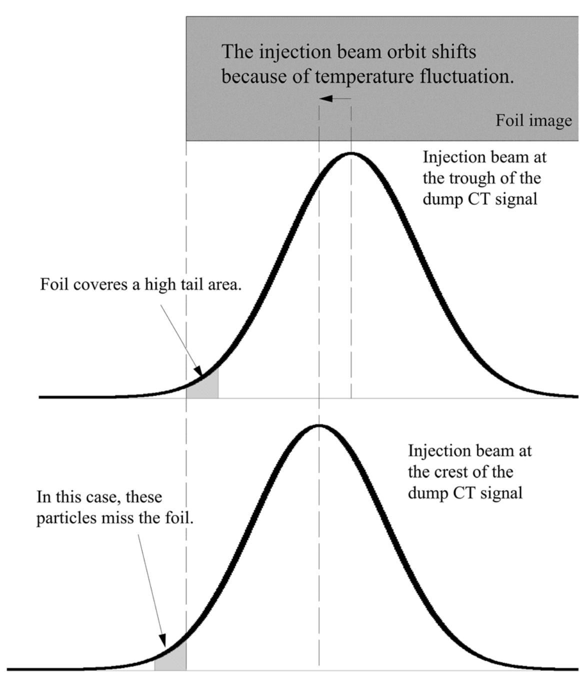


**Fig. 4** Relation between injection beam profile and foil position

the injection beam orbit. Consequently, when the injection beam is in the inner position, the foil can cover a relatively large area of the beam profile. In contrast, if the beam injects in the outer position, more particles in the tail of the profile would miss the foil and fail in the charge exchange.

## Evaluation of variations in injection beam position

We evaluated the variations in the injection beam position (relative to the stripper foil) using the data from Fig. 2. As mentioned above, we usually apply FFT (to the CT data) at a frequency of 1.2 MHz, which corresponds to the time structure of the injection beam, to the raw data. The absolute value of the charge-exchange efficiency is measured by the CT and multiwire profile monitor of the injection dump line at a certain period [10]. In this case, we used the efficiency of 99.61%, which was measured on 17th Dec. 2018. Therefore, 0.39% of the injection beam was not injected and was delivered to the injection dump. We considered that 0.39% of the beam corresponds to the trough in the CT data in Fig. 2. Furthermore, the difference between the crest and trough, or vice versa, is defined as the fluctuation range. According to the data from 3:00 to 5:00 in Fig. 2, the average value of the peak height is $4.87 \times 10^{-5} \pm 0.24 \times 10^{-5}$ and average value of the fluctuation range is $0.24 \times 10^{-5} \pm 0.04 \times 10^{-5}$. From these values, the ratio of the fluctuation range to the peak height is 0.049. Here, it is considered that the signal level at the trough corresponds to 0.39% of the total injected beam current; thus, the fluctuation range for the total injected beam current is calculated as 0.39% × 0.049 = 0.019%. This value is quite small, and all the CTs in the RCS circulating beam line cannot detect such small signal fluctuations.

Next, we investigated the magnitude of the orbit fluctuation effect on the efficiency. As shown in Fig. 4, when the orbit fluctuates outward, the hatched part in the profile protrudes from the foil. The area of the hatched part corresponds to the reduction in the injection beam current. The beam profile on the foil is measured by a multiwire profile monitor [11]. During a typical operation, the center of the injection beam is adjusted to a position 9.0 mm from the horizontal edge of the foil. Figure 5 shows the

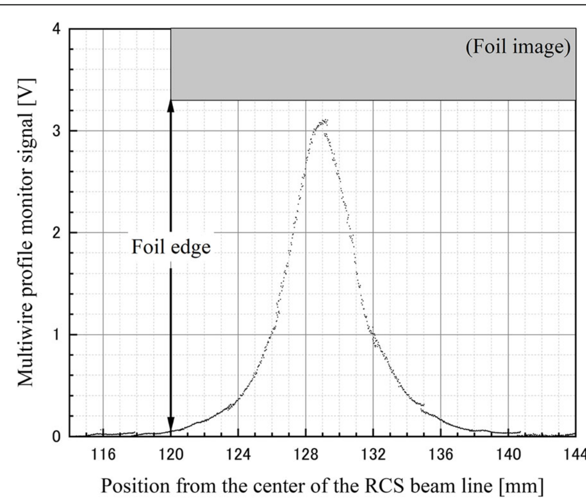


**Fig. 5** Injection beam profile and foil position

relation between the measured profile data and foil position. The interval between each measurement point is 0.03 mm.

The half-width of the profile in Fig. 5 is larger than 9.0 mm, indicating that there was a beam away from the foil, and the charge-exchange efficiency would change if the center of the injection beam fluctuates. From the profile data, the center of the injection beam is at 128.96 mm and edge of the foil is at 119.96 mm from the RCS circulating beam center. The average value around the foil edge was calculated as 0.048 ± 0.019 V per measurement point. If we define the full width of the profile as ±15 mm from the data, the summation of the entire signal gives 602.99 V. Thus, the ratio of the signal at the foil edge to the summation of the entire profile signal is 0.0079% ± 0.0032%. As the interval between each measurement point is 0.03 mm, the amount of the injection beam current would change at a rate of 0.0026% per 0.01 mm. Therefore, to reduce the beam current by 0.019%, the injection beam must move by 0.072 mm ± 0.032 mm. This error was evaluated based on the precision of the profile monitor and standard deviations of the CT data.

## Results and discussions

From the above considerations, it was found that the injection beam orbit can be distorted by the fluctuation in the cooling water temperature, which would result in a 0.072 mm displacement of the injection point. However, this value is less than the measurement precision of the beam position monitors in the L3BT line, and we could not identify any periodic signals. The black line in Fig. 6 shows the beam position data of the L3BT monitor. Although the position data was taken every second, large fluctuations were observed between each shot. Therefore, to reduce the effect of short-cycle fluctuation noise, a moving average of 10 s was applied. The red line in Fig. 6 denotes the moving average. With this treatment, the fluctuations in the data were reduced to approximately 20%, although there were no periodic signals in the averaged position data. The averaged position data of all position monitors in the L3BT are shown in Fig. 7. We carried out the FFT analysis on these data around the frequency range of the temperature oscillation; however, we did not find any clear peak in the spectra. This result suggested that the CT of the injection dump has more sensitivity toward the

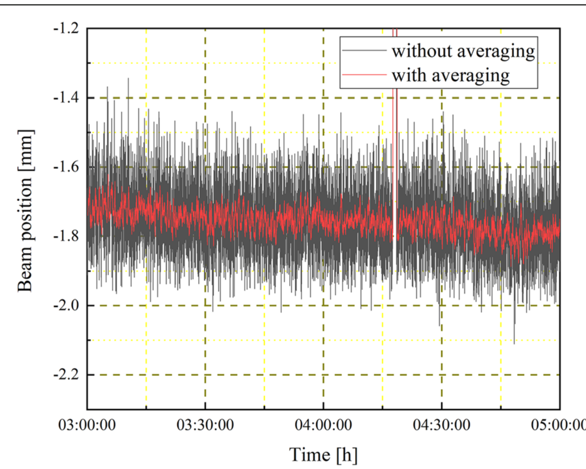


**Fig. 6** Beam position data at L3BT with and without the application of moving averages

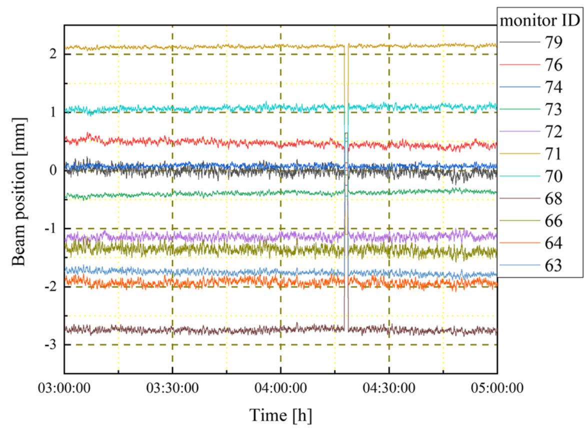


**Fig. 7** Beam position data of all position monitors in L3BT

orbital stability. However, the estimated value includes some simple assumptions, and there are many ambiguities in the accuracy of the absolute value. Therefore, we need more precise data of the measurement condition to decide the absolute value of the beam distortion.

Next, we evaluated the magnetic field distortion due to the oscillations in the cooling water temperature using the displacement of the injection point and transfer matrix. On the RCS side of the L3BT, there are two dipoles, septum magnets, and bump magnets that bend the beam with a dipole magnetic field (Fig. 3). In reality, the magnetic field response of each magnet to the cooling water temperature change differs. However, we assumed that the dipole magnetic field strength changes at the same rate in all dipole magnets. We also assumed that the ratio of the quadrupole magnet field error would be the same as that in the dipole case. Under these assumptions, we estimated the change in the dipole magnetic field required for the orbit of the injection point to be displaced by 0.072 mm using the transfer matrix. The result indicated that the magnetic field error would be $1.63 \times 10^{-5}$. We also estimated the beta-function modulation due to the field error of the above assumption. Consequently, the square root of the beta-function, which is proportional to the beam size, changes by approximately $4.65 \times 10^{-5}$. If we assume that the profile has a Gaussian distribution, this value corresponds to the change in the standard deviation, and the tail change would be in the order of $10^{-7}$. This value is negligible compared to the effect of the dipole field distortion. To confirm the above consideration, we roughly estimated the magnetic field variation of the L3BT dipole magnet due to the temperature change. A yoke of the L3BT dipole magnet is composed of an electromagnetic soft iron, and its coefficient of linear thermal expansion is approximately $1.2 \times 10^{-5}$ /K. As the temperature change is 3.4 °C, the width of the magnet gap changes at a rate of $4.08 \times 10^{-5}$. In the first-order approximation, the magnetic field is inversely proportional to the gap width. Therefore, the magnetic field error is estimated to be $4.08 \times 10^{-5}$. This value is approximately 2.5 times larger than the result of the analysis using the profile monitor data. One reason for this discrepancy might be the difference between the temperature of the cooling water and that of the magnet itself. The temperature variation range of the magnet is smaller than that of the cooling water because of its large thermal capacity. For a more accurate evaluation, it is necessary to measure the magnetic field of the actual magnet by changing the cooling water temperature; however, this is impossible because the magnet is already installed in the tunnel. In summary, it was confirmed that even with very simple assumptions, such as those in this study, the magnetic field evaluations from two cases are consistent within the same order of magnitude. Therefore, we consider that the change in the cooling water temperature is one of the major causes of the efficiency fluctuation.

## Conclusions

J-PARC RCS continues to deliver high-intensity proton beams for various physics programs. To obtain good results with J-PARC, the accelerator needs to supply as stable a beam as possible. We have monitored various parameters of the RCS to evaluate the stability of the beam and found that the charge-exchange efficiency fluctuates periodically. By analyzing other parameters, we found that these fluctuations are synchronized with the oscillations in the cooling water temperature. Based on the amount of the particles that failed in the injection and beam profile at the injection point, we evaluated the displacement of the injection beam to be 0.072 mm in total. From the accelerator operation viewpoint, even if the injection point shifted by this value, the beam current in the RCS would change by only 0.019%, which is negligible.

Since the present beam position monitor is designed with the sensitivity required for monitoring the beam for stable operation, such a minute amount cannot be detected. Conversely, from the results of this evaluation, the CT data of the injection dump may provide more information on the orbital stability. However, because the current data contains some ambiguities and errors, it is desirable to improve the measurement system and magnetic field evaluation for a more detailed discussion. Nonetheless, it is considered that the change in the cooling water temperature is one of the major causes of the efficiency fluctuation.

### Abbreviations

RCS: Rapid Cycling Synchrotron; J-PARC: Japan Proton Accelerator Research Complex; MR: Main Ring synchrotron; MLF: Material and Life science experimental Facility; $H^-$: Negative hydrogen ion; $H^0$: Neutral hydrogen atom; CT: Current transformer; ppp: Protons per pulse; L3BT: Linac 3-GeV RCS beam transport line

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### Authors' contributions

KY wrote the manuscript, coordinated the work, and analyzed the data. SH and PKS provided the trend data of the injection dump and cooling water. PKS and MY provided the multiwire monitor data. KM and KO provided the data of the beam position monitors. MY and TN provided the foil information. KF, YY, and KS provided the information on the cooling water system. The author(s) have read and approved the final manuscript.

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### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

### Competing interests

The authors declare that they have no competing interests.

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