DYNAMIC CORRECTION OF EXTRACTION BEAM DISPLACEMENT BY FIELD RINGING OF EXTRACTION PULSED KICKER MAGNETS IN THE J-PARC 3-GEV RCS

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Abstract

The 3-GeV rapid cycling synchrotron (RCS) of J-PARC is designed for a high-intensity output beam power of 1MW. The RCS is extracted two bunches by using eight pulsed kicker and three DC septum magnets with 25Hz repetition. The extracted beam is simultaneously delivered to the material and life science experimental facility (MLF) as well as the 50-GeV main ring synchrotron (MR). The kicker magnets have the ringing of flat-top field and the ringing causes the position displacement. The displacement is big issue because it causes an emittance growth of the extracted beam directly. In the beam tuning, we performed a timing scan of each kicker magnet by using a shorter pulse beam in order to understand the characteristics of ringing field. We then carefully optimized the trigger timings of each kicker for the ringing compensation. We have successfully compensated the extracted beam displacements to (min., max.) = (−1.1 mm, +0.6 mm) as compared to (–14 mm, +10 mm) with no ringing compensation. The procedure for ringing compensation and experimental results are reported in this paper.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multipurpose proton accelerator facility [1,2], comprising three accelerator facilities that are a 400-MeV LINAC, a 3-GeV rapid cycling synchrotron (RCS), and a 50-GeV main ring synchrotron (MR), and three experimental facilities that are a materials and life science experimental facility (MLF), a hadron experimental hall, and a neutrino beam line to Kamioka. In this chain of accelerators, the RCS has two functions as a proton driver to produce pulsed muons and neutrons at the MLF and as an injector to the MR, aiming at 1-MW output beam power. The RCS was beam-commissioned in October 2007 and the output beam power has been steadily increasing following progressions in the beam tuning, hardware improvements and the realistic numerical simulations [3,4,5]. After the LINAC had been upgraded output energy from 181 to 400-MeV by installation of ACS linac section in 2013 summer-autumn maintenance period, the RCS has successfully achieved output beam power of 300-kW for user operation and demonstrated 550-kW equivalent intensity with beam loss mitigation in our beam study [6]. In 2014 summer maintenance period, the Ion Source (IS) and RFQ in LINAC were replaced in order to upgrade a peak current from 30 to 50 mA. After upgrading the peak current from LINAC, the RCS started a beam tuning of the designed 1-MW intensity in October 2014. In first trial of the designed 1-MW intensity, we achieved 770-kW equivalent intensity [7]. In higher intensity beams, the trip of RF power supplies was happened. In December 2014 and January 2015, we will retry a beam tuning of 1-MW intensity after the treatment for the RF issue.

As shown in Fig. 1, the RCS extraction system consists of eight pulsed kicker magnets and three DC septum magnets. The extracted beam of two bunches is simultaneously delivered to MLF and MR with a repetition rate of 25 Hz. The pulsed kicker magnet has a ringing of flat-top field and the ringing causes position displacements to the extracted beam for horizontal plane. In this paper, the configuration and field ringing of kicker magnet are introduced and the effect on extracted beam is mentioned. The measured beam displacements by kicker timing scan and the procedure for kicker ringing compensation are reported. Finally, the results of the compensation are described.

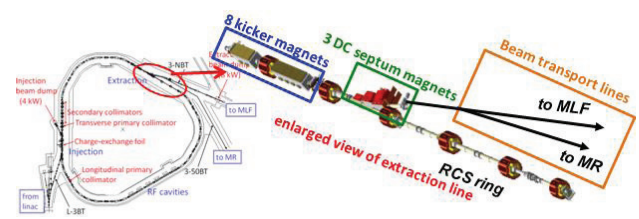

Figure 1: RCS and extraction line

EXTRACTION KICKER MAGNET

The detail configuration and field measurement of extraction kicker magnet and power supply have already been described in reference [8]. In this section, the configuration and measured magnetic field are briefly introduced.

Configuration

Kicker magnet consists of twin-C distributed Ferrite core with twenty units and two conductors in vacuum and the power source consists of two Thyratrons, PFN & loading cables and matching registers. Schematic diagram of kicker magnet system is shown in Fig. 2. Kicker magnet as shown in Fig. 2 is driven by two Thyratrons via two conductors. Operation charging voltage of Thyratron is 60 kV and exciting current of magnet by two Thyratrons is 6

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ISBN 978-3-95450-173-1

kA. As shown in Fig. 2, two conductors have exciting current in the opposite direction. The eight kickers have three types (S:3, M:2 and L:3), which are identified by vertical aperture gap of 153 mm (S: Nos.1, 7 and 8), 173 mm (M: Nos.2 and 6) and 199 mm (L: Nos. 3, 4 and 5).

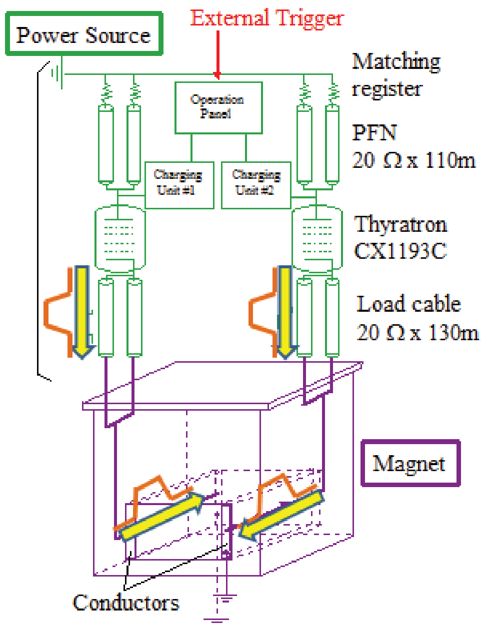

Figure 2: Schematic diagram of kicker system

Measured magnetic field and ringing field

Twin-C core and calculated magnetic fields of kicker in the conditions of one (upper graph) and both (lower graph) side excitations are shown in Fig. 3. The measured fields are shown in Fig. 4. The measured fields in the condition of right and another left side excitation are A and B as shown by the upper graph in Fig. 4, respectively. Field C is the summed field of both A and B. Field D in Fig. 4 is the measured field in the condition of both side excitations. Field C is a good agreement with D. So, field D is created by combination of field A and B. It was found that the disturbance of the flattop as shown by the lower graph in Fig. 4 is caused by two reasons. One is the impedance mismatch between load cables and corresponding magnet and it is shown in the measured field A. The other is the effect of the magnetic field induced by the penetrated magnetic flux from the opposite side of the ferrite core and it is shown in the measured field B. As a result, the flattop of the kicker magnetic field showed a ringing structure such as measured filed D.

EXTRACTION BEAM QUALITY

The ringing field causes the different beam center position between two bunches and the beam displacements in first bunch. So, the flattop uniformity of the kicker magnetic field affects a quality of the extracted beam directly. In a first beam commissioning of the RCS, the required flatness of the flattop is 2% in the time length of 840 nsec in order to extract the two bunches as compared with the measured field flatness of 6%. In order to compensate the distortion, the timing adjustment of the each kicker magnet was attempted. The timing of four out of eight kickers was modified to cancel out the peaks and valleys of the flattop. The trigger timing of first group (Nos. 1, 3, 5, and 7 kickers) was fixed. On the other hand, the trigger timing of second group (Nos. 2, 4, 6, and 8 kickers) was delayed for about 130 nsec. This delay condition calls as “reference delay”. The flatness of 2% was achieved in the time length of 850 nsec, which satisfies the requirement in first beam commissioning. These results have already discussed in reference [9].

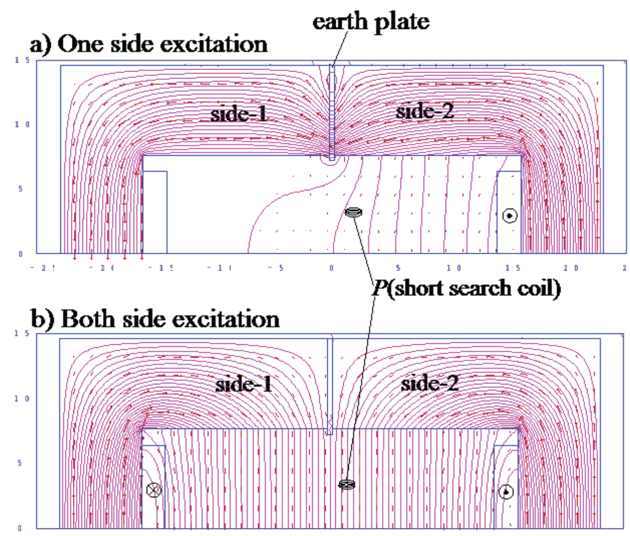

Figure 3: Calculated field and twin-C core of kicker. One side excitation case : a); both side excitation case : b). *P* is a short search coil position in field measurement.

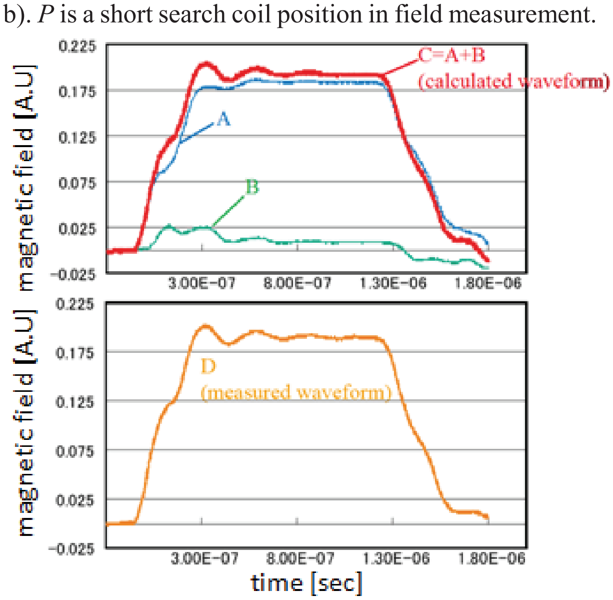

Figure 4: Time structures of measured magnetic field. Filed A and B in the upper graph are the measured fields in right and left side excitation. Field C in the upper is the summed field of both A and B. Field D in the lower is the measured field in condition of both side excitations.

ISBN 978-3-95450-173-1

Beam displacement measurement caused by kicker field ringing

In a user operation up to June 2013, eight kickers have been operated in trigger timing delay of 130 nsec between first and second kicker group. A higher quality of extracted beam is required in a stage of beam tuning for high intensity in order to reduce the shock wave at a neutron target and the emittance growth of MR injection beam. To understand the flattop uniformity on total field of kickers, the uniformity was measured as beam position displacements by using a shorter pulsed-beam and trigger timing scan of entire kickers. The beam bunch length of 30 nsec is shorter than normal one of 150-200 nsec in order to measure the ringing structure. The measured beam displacement Δx is shown in Fig. 5. Fortunately, there was no much deference of beam center positions between first and second bunches. However, the measured beam displacements in first bunch was a range from −5.5 mm to +3.3 mm, corresponding to −1.6% and +0.75%. As the result, the ringing cannot be compensated by only simple trigger delay of 130 nsec between two groups. So, it is very important to directly measure the time structure of beam displacement by trigger timing scan with shorter pulsed beam for understanding the effect on kicker ringing.

In order to further compensate the kicker ringing, the trigger timing of each kicker must be optimized. However, the time structure of kicker ringing is not simple. In fact, eight kickers consist of three types with different core gap corresponding to strength of magnetic field and each kicker has different betatron phase-advances. Therefore, it is very important to understand the effect on the beam position and the ringing structure kicker-by-kicker. And then, the trigger timing of each kicker should be optimized by the beam-based data for the ringing compensation.

Beam-based position displacement response measurement kicker-by-kicker

The beam-based measurements of beam displacement response kicker-by-kicker were performed by using a shorter pulsed-beam and trigger timing scan of single kicker. The trigger timing of a single kicker was swept kicker-by-kicker and the timing of other seven kickers was fixed where the extracted beam position was measured by BPM at the extraction beam transport line. Each data of the trigger timing scan for eight kickers (Nos.1 to 8) is shown in Fig.6. The time structure of each ringing was clearly measured and the different structure between each kicker was understood well. To check whether these data is right or not, we measured the beam displacements by entire timing scan in the other condition that timing delays of Nos.1, 4, 7 and 8 are 10, 35, 10 and −10 nsec. The measured beam displacements by entire timing scan were compared with the calculated ones based on scan data kicker-by-kicker for two data of different timing delay. The compared results are shown in Fig. 7. The calculated beam displacements based on scan data kicker-by-kicker is a good agreement with the measured ones by entire trigger timing scan. So, we can discuss with timing optimization of each kicker based on scan data kicker-by-kicker for the ringing compensation

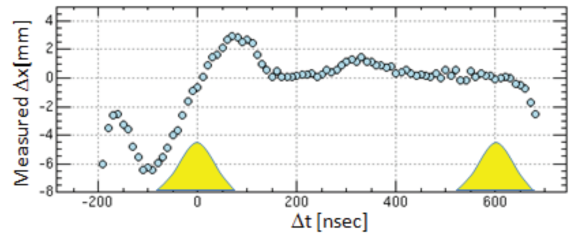

Figure 5: The measured beam displacement Δx (dots of light blue) by trigger timing scan of entire kickers and normal two bunched beams (yellow). Left and right bunches are first and second ones, respectively.

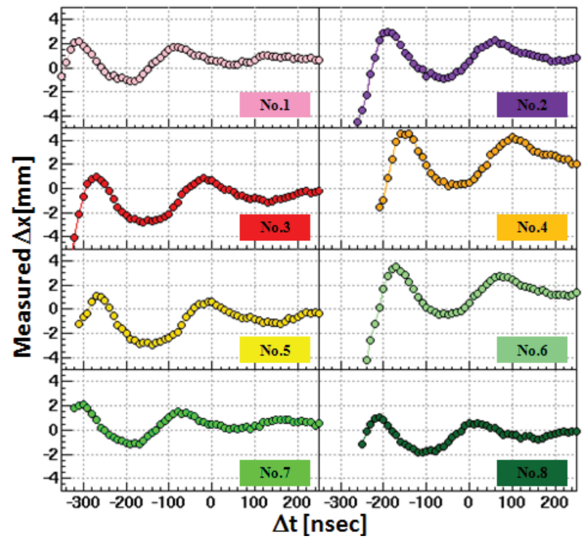

Figure 6: The measured beam displacement Δx[mm] by trigger timing scan of Δt[nsec] kicker-by-kicker. Δt of 0 is bunch center of first bunch.

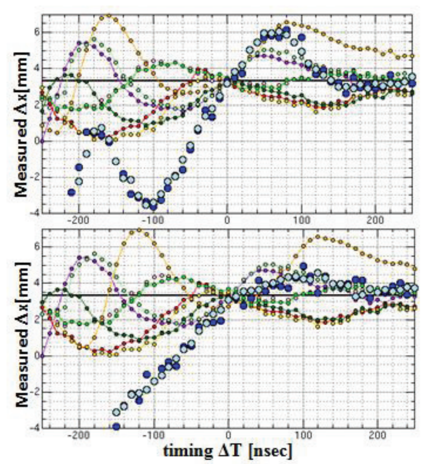

Figure 7: The calculated beam displacements (blue dots) based on scan data kicker-by-kicker and the measured beam displacements (light blue dots) by entire trigger timing scan of eight kickers. Δt of 0 is bunch center of first bunch. The upper and lower graphs are the calculated and measured displacements for different timing delays kicker-by-kicker in the upper graph is fixed.

ISBN 978-3-95450-173-1

Trigger timing optimization of each kicker for the ringing compensation

Search of the optimized kicker's trigger timing were performed based on timing scan data kicker-by-kicker. The time structure of each kicker ringing is not simple and we could not adapt a beautiful method such as "least-square method" for optimization of trigger timing kicker-by-kicker. So, we tried to search the trigger timing of each kicker for further ringing compensation by "brute force method". The trigger delays of each kicker for reference delay (1) and optimized delay from reference one (2) are described in Table 1. Beam displacements in the case of no trigger delay (0), reference delay (1) and optimized delay (2) are shown in Fig. 8. In first bunch length, (min., max.) of beam displacements with trigger delay of (0) and (1) are (−14 mm, +10 mm) and (−5.5 mm, +3.2 mm), respectively. After the optimization of trigger delay that is (2), (min., max.) of beam displacements are (−1.1 mm, +0.6 mm). As the result, we have successfully achieved to compensate further the beam displacement of extracted first bunch from (−5.5 mm, +3.2 mm) of reference delay to (−1.1 mm, +0.6 mm) of optimized delay, corresponding to the field distortion degree of (–0.28%, +0.15%).

The extracted beam profile of first and second bunch for trigger delays of (0) to (2) were measured by a multi wire profile monitor at the extraction beam transport line for confirming the optimization of trigger delay kicker-by-kicker. These measured beam profiles and fitted Gaussian functions are shown in Fig. 9. The center position displacements of measured beam profiles between first and second bunch made no differences among three timing delay patterns. On the other hand, the measured beam width of first bunch in trigger delay patterns of (0) and (1) is wider than that of second bunch. But, the fitted width σ_x of the measured beam profile for first bunch after the optimization of timing delay (2) kicker-by-kicker was a good agreement with the width for second bunch.

The extracted beam displacements caused by the kicker field ringing were compensated well and the good beam quality of extraction beam was successfully achieved by using the timing scan data kicker-by-kicker. So, our procedure fills the role for compensation of the kicker field ringing as a good example.

Table 1: Trigger Delay Kicker-by- Kicker

Kicker	Trigger delay Δt (1)	Trigger delay Δt (2)
No.1	0 nsec	60 nsec
No.2	0 nsec	-20 nsec
No.3	0 nsec	50 nsec
No.4	0 nsec	30 nsec
No.5	0 nsec	200 nsec
No.6	0 nsec	-30 nsec
No.7	0 nsec	50 nsec
No.8	0 nsec	-40 nsec

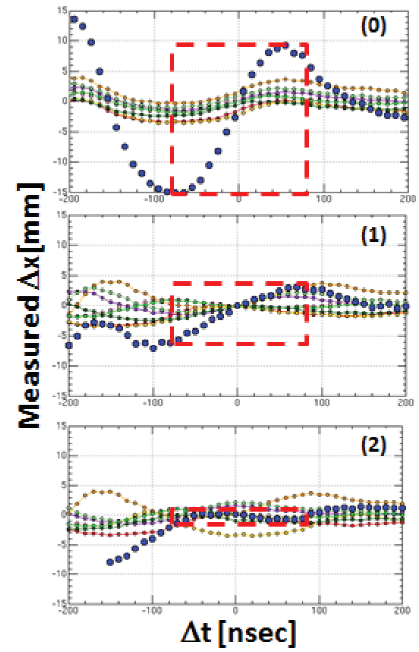

Figure 8: Beam displacements (blue dots) with no compensation (upper graph), compensation by reference delay (center graph) and compensation by optimized delay (lower graph) in the region of first bunch. Rectangle of red dash line is first bunch length.

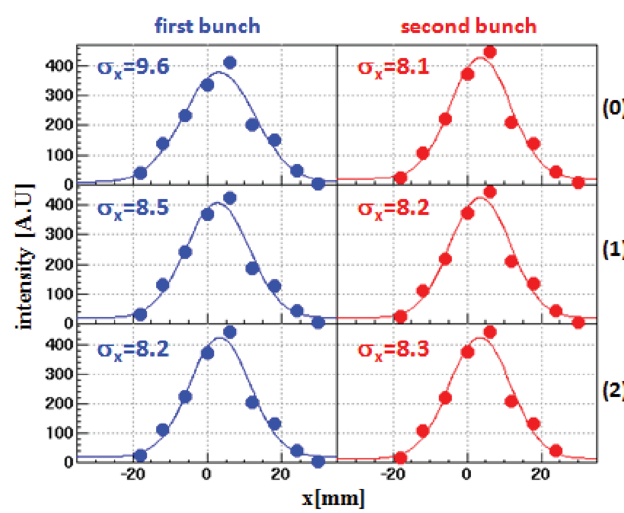

Figure 9: The measured beam profile of extracted first (left) and second bunch (right). Upper, center and lower graphs are the measured beam profile in the trigger delay patterns of (0), (1) and (2), respectively. Lines are fitted Gaussian functions and σ_x[mm] is analyzed one sigma by the function.

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EXTRACTION BEAM STABILITY

We found that it is very important to keep the trigger delay kicker-by-kicker for extraction beam quality. However, there is a gradual change in Thyratron condition where Thyratron output timing has a drift over a period of minutes by lifetime or bad condition of Thyratron. In fact, the extracted beam in a user operation caused the beam displacement of more than 25 mm when Thyratron output has had a drift. Therefore, online monitor system of output current for all Thyratrons were developed. In the system, output current Thyratron-by-Thyratron was monitored and the output timing was analyzed online. If Thyratron output timing has a difference of more than |10| nsec from a reference one, the output timing is automatically corrected by the trigger timing. We have achieved to keep the extraction beam stability for beam delivering to the MLF and the MR.

CONCLUSION

The J-PARC 3-GeV RCS is extracted two bunched beam as high-intensity proton beam by using eight pulsed kicker and three DC septum magnets with 25Hz repetition. The extracted beam is simultaneously delivered to MLF as well as the 50-GeV MR. The kicker magnets have the ringing of flat-top field caused by the magnet configuration and the ringing causes the beam position displacement of the extraction beam. The displacement is big issue because it causes an emittance growth of the extracted beam directly.

In a first beam commissioning started since October 2007, the required flatness of the flattop is 2% in the time length of 840 ns in order to extract the two bunches as compared with the measured field flatness of 6%. For compensation of the kicker ringing, eight kickers had in trigger timing delay of 130 nsec between first (Nos.1, 3, 5 and 7) and second kicker group (Nos.2, 4, 6 and 8). The flatness of 2% was achieved in the time length of 850 nsec In order to understand the flattop uniformity or the ringing structure by total field of kickers, the uniformity was measured as beam position displacements by using a shorter pulsed-beam of 30 nsec and trigger timing scan of entire kickers. In the region of first bunch length, we found that (min., max.) of beam displacements were (−5.5 mm, +3.2 mm), corresponding to the field distortion degree of (−1.6%, +0.75%).

In a user operation up to June 2013, eight kickers have been operated in the trigger timing delay. However, a higher quality of extracted beam is required in a stage of beam tuning for high-intensity operation in order to reduce the shock wave at a neutron target and the emittance growth of MR injection beam. Therefore, it is necessary to further compensate the effect on the kicker ringing. In order to further compensate the kicker ringing, the beam-based measurements of beam position displacement response kicker-by-kicker were performed by using a shorter pulsed-beam and trigger timing scan of single kicker. After that, search of the optimized kicker's trigger timing were performed based on the timing scan data kicker-by-kicker. As the result of trigger-timing optimization, we have successfully achieved to compensate further the beam displacement of extracted first bunch from (−5.5 mm, +3.2 mm) to (−1.1 mm, +0.6 mm), corresponding to the field distortion degree of (−0.28%, +0.15%). Additionally, the beam width of the measured beam profile for first bunch was a good agreement with the width for second bunch. The extracted beam displacements caused by the kicker field ringing were compensated well and the good beam quality of extraction beam was successfully achieved by using the timing scan data kicker-by-kicker.

For extraction beam stability, online monitor and automatic correction system for Thyratrons output timing were developed. We have achieved to keep the extraction beam stability for beam delivering to the MLF and the MR.

We have achieved to keep the extraction beam quality and stability without improvement of kicker magnet devices and new installation of correction magnet. Our procedure fills the role for compensation of the kicker field ringing as a good example.

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ISBN 978-3-95450-173-1