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UPGRADE OF THE INJECTION KICKER SYSTEM FOR J-PARC MAIN RING

T.Sugimoto*, K.Fan, K.Ishii, H.Matsumoto, KEK, Ibaraki, Japan

Abstract

Four lumped inductance injection kicker magnets for the J-PARC main ring (MR) produce a kick of 0.1096 T·m with a 1% to 99% rise-time of about 400 nsec. A residual field of about 6 % of the flat-top exists at the tail of the pulse due to an impedance mismatching. The residual field is required to be suppressed less than 1% to reduce injection losses. For a higher intensity beam operation, the kicker rise-time of less than 300 nsec is required to inject longer beam bunches which reduces a space charge effect. During the long shutdown in FY2013,140 Ω resistor and 7 nF capacitor were connected to the thyratron to improve the post-pulse shape. In addition, an optimization of a capacitance in the matching circuit was carried out to optimize the waveform. As the result, the rise-time of 195 nsec and the residual tail field of 2 % were achieved. However, another reflection peak of about 9 % is appeared. We plan to compensate the effect of the new peak by using a new small kicker magnet. This paper discusses the detail of the circuit and the beam test results.

INTRODUCTION

J-PARC (Japan Proton Accelerator Complex) consists of three accelerators, a 400-MeV Linac, a 3-GeV Rapid Cycle Synchrotron (RCS) and a 30-GeV Main Ring (MR). The MR provides a high intensity proton beam to the long baseline neutrino experiment (T2K) and the hadron experiments. During 2013, 220 kW beam has been provided to the neutrino experiment [1]. For the higher precision measurement of the neutrino oscillation and the observation of the CP violation of the neutrino, a higher power beam operation is required. Two scenarios are being considered; one is to increase the beam current, the other is to increase a repetition rate of the MR. For former, it is necessary to use 2nd harmonic RF cavities to mitigate the instability due to the space charge effect [2]. However, there is not enough margin for a rise-time of a injection kicker pulse of the MR to modify the longitudinal bunch shape. In addition, it is important to reduce a beam loss which introduces a radioactivation of the instruments installed in the accelerator tunnel. In 2013, average injection loss was approximately 200 W. A major source of a loss during injection period is a coherent oscillation of the circulated beam deflected by a residual field of the injection kicker [3]. Therefore, an upgrade of the injection kicker is one of the key issues to realize the higher intensity operation.

MR INJECTION KICKER SYSTEM

Figure 1 shows the injection section of the MR. Proton bunches are extracted from RCS, and transported via a beam transport line (3-50BT). Two types of septum magnets and four injection kicker magnets are equipped to introduce proton bunches to the circular orbit.

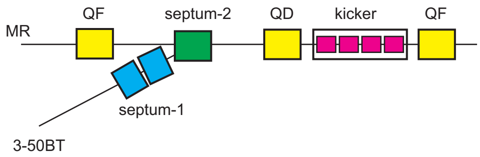

Figure 1: Schematic diagram of the injection section of the J-PARC MR.

The kicker magnets consist of four identical window frame lumped inductance kickers installed in a vacuum chamber. Each kicker is driven by two independent power supplies to realize a short rise-time. A Ni-Zn ferrite core (CMD10 provided from Ceramic Magnetics Inc.) was chosen as a return yoke because of the high saturation flux density and the high Curie temperature.

The equivalent circuit of the kicker system is shown in Fig. 2. An inductance of each magnets was designed as 600 nH. Including a stray inductance of a copper plate connected between the high voltage feed-through and the coil, however, the total inductance of the magnet (L_1) was estimated as about 1 μH. To match with the transmission cable with a characteristic impedance of 9.7 Ω measured by a time domain reflectometry method, a capacitance (C_1) should be10.6 nF which results in a large rise-time (it is estimated as more than 500 nsec using a SPICE software). Furthermore, this mismatching also induces a reflection peak. The optimized values for the circuit are indicated in Fig. 2.

Non-inductive ceramic resistors and ceramic capacitors were installed in individual boxes filled with nitrogen. They were mounted on the vacuum chambers and connected to the coils for the impedance matching. The kicker system has been operated since December 2011 [4]. However, severe discharge problems of the ceramic resistors were found on March 2012. We have overcome the problem by applying a brazing technology to attach electrodes to the end of ceramic resistor [5].

A waveform of the excitation current measured by a current transformer is shown in Fig. 3. Four injection timing signals (K1-4, 40 msec interval) are synchronized to the extraction timing of the RCS. For each timing, an excitation current is transmitted to the magnet to deflect two proton bunches into the circular orbit. Nominal deflection angle is 8.5 mrad for 2.7 kA excitation current. The measured

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* takuya.sugimoto@j-parc.jp

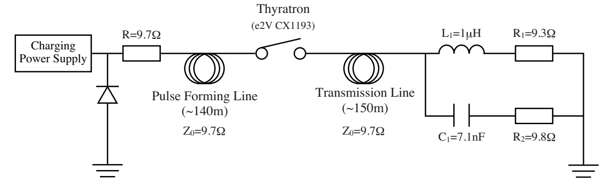

Figure 2: Equivalent circuit of the injection kicker system.

rise-time is approximately 400 nsec (from 1% to 99%). Circumference of the MR is 1567.5 m and the revolution period is 5.38 μs before acceleration. Interval of each bunches is 597.7 nsec, and the bunch length is about 150 nsec with using fundamental harmonic RF cavities (h=9). The rise-time is required to be about 200 nsec because the longitudinal bunch length will be increased up to 400 nsec by adding a 2nd harmonic RF cavity to reduce the space charge effect.

As shown in the waveform, there is a tail of about 5 % for 1 μs duration and a reflection peak of about 6 % at 3.5 μsec. Due to this residual field, some of the circulating bunches were kicked additionally (especially No.1 bunch at K3 timing, No.1-3 bunches at K4 timing). This extra-kick becomes a source of a transverse coherent oscillation which induces an emittance blow-up and a beam loss during the injection period. To damp the oscillation, two kinds of beam feed-back system have been equipped [3] [6]. However, the injection loss is still dominant for the total amount of beam loss for the MR.

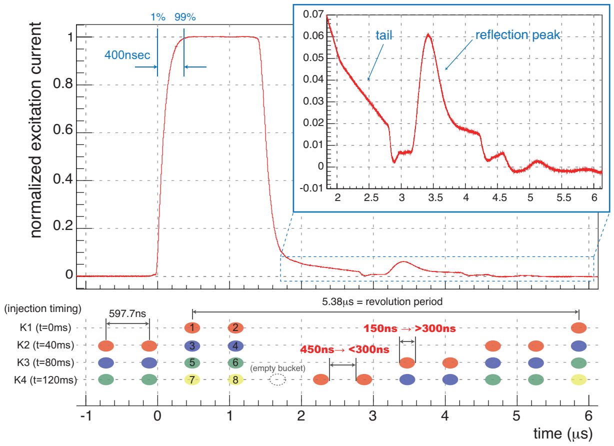

Figure 3: A measured waveform of the excitation current of the injection kicker and the position of injected bunches for each injection timings (K1-4).

CIRCUIT MODIFICATION

During a long shutdown in 2013, two additional circuits shown in Fig. 4 (indicated as dotted rectangles) were attached to the thyratron housing. Furthermore, the capacitance of C_1 was optimized to adjust the rise-time and the reflection peak.

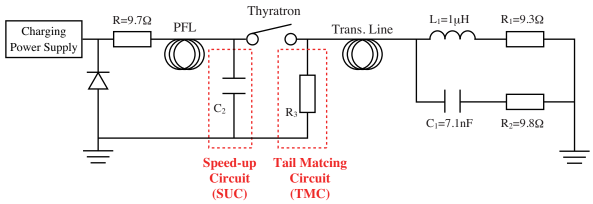

Figure 4: Upgraded circuit.

(1) Tail Matching Circuit (TMC)

According to the SPICE simulation study, the pulse tail was caused by a impedance mismatching due to a conduction loss of the thyratron and a resistive component of the thyratron housing and the high voltage connectors. To improve the mismatching, a resistor (R_3) was attached to the cathode of the thyratron. Figure 5 shows a measured waveform with respect to the various R_3. As shown in the figure, the pulse tail was reduced less than 1% successfully with R_3<140 Ω. However, the flat-top value of the pulse was also decreased. Considering the trade-off between the tail reduction and the flat-top drop, R_3=140 Ω was chosen.

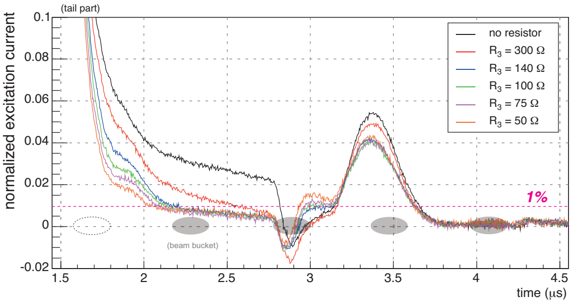

Figure 5: Measured waveform of kicker excitation current for various resistors (tail part of the pulse is expanded.).

(2) Speed-up Circuit (SUC)

Reverse current flows into a capacitor attached to the anode of thyratron at the leading and trailing edge of the pulse. This current also flows into the magnet and then makes an overshoot waveform which is effective to improve the rise-time. The upper two figures of Fig. 6 show the waveforms measured with a SUC capacitor (C_2). The leading edge and the reflection peak were changed by scanning C_1 with fixed C_2=7 nF. The lower figure of Fig. 6 shows the rise-time and the fraction current of the reflection peak as a function of C_1. Optimization of C_1 was carried out to control the rise-time and the reflection peak. As the results, the rise-time of 195 nsec with the original peak fraction of 6 % were achieved with C_1=6.5 nF. While the requirement of the rise-time was satisfied with this condition, another reflection peak of 9 % which corresponds to a reflection at C_2 was appeared before the original reflection peak.

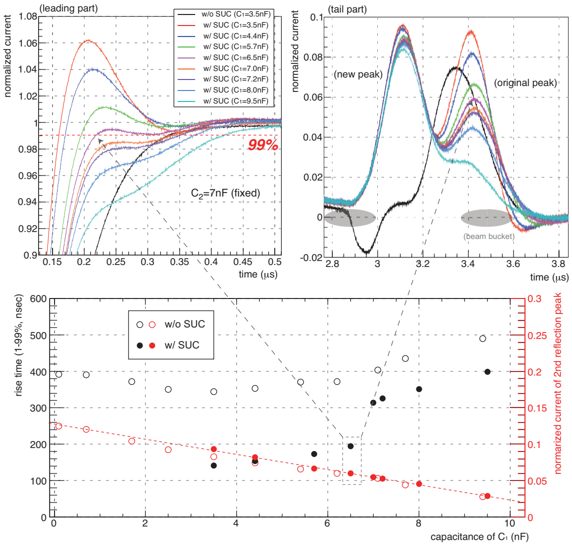

Figure 6: Measured waveform of kicker excitation current (upper) and measured rise-time of the kicker pulse as a function of capacitance in matching circuit (lower).

BEAM TEST RESULT

In Fig. 7, three kicker waveforms are summarized. Although the tail was successfully reduced by R_2, the new reflection peak which is bigger than the original one was appeared. To estimate the effect of the modifications, a beam intensity were measured by a DCCT equipped in the MR. As shown in Fig. 8, a part of the beam was lost at K3 and K4 injection timing due to the injection oscillation. While the beam loss at K4 which corresponds to No.1 bunch deflected by the tail was improved after attaching R_2 (red line), it was increased after attaching C_2 because No.2 bunch was deflected by the new reflection peak (blue line). The beam loss at K3 timing was almost unchanged after the modification.

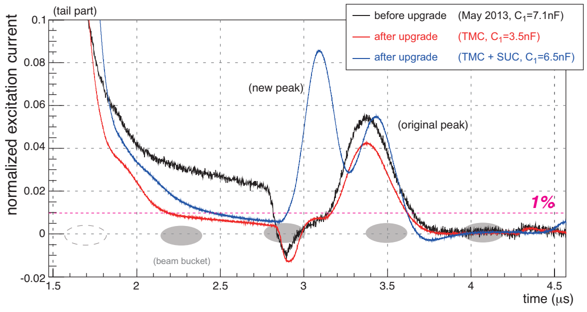

Figure 7: Tail part of kicker waveform.

To suppress the injection oscillation, two beam feedback systems (bunch-by-bunch and intra-bunch feedback) have been equipped in the MR [3] [6]. In 2014, a performance of the intra-bunch feedback system (Intra-B FB) was measured by using the high intensity proton beam (220 kW equivalent). The result listed in Table 1 indicates that the feedback system suppressed the coherent oscillation effectively even if the additional oscillation was induced by the new reflection peak. Furthermore, a new kicker magnet is planed to be installed in the injection section of the MR at about 80 m downstream from the injection kicker magnet to compensate the extra-kick of the reflection peaks [7].

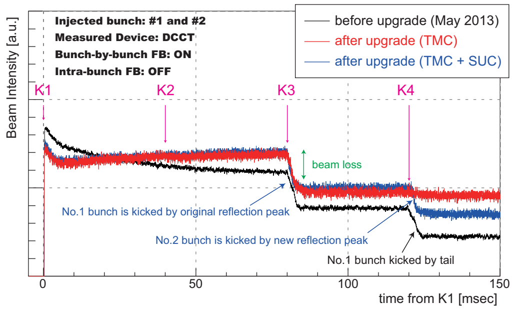

Figure 8: Beam intensity measured by DCCT.

Table 1: Relative value of injection beam loss for high intensity beam test.

Intra-B FB	TMC+SUC	no circuit
ON	0.6	0.5
OFF	1.3	1

CONCLUSION

Introducing two additional circuits and optimizing the capacitance of the matching capacitor, the pulse waveform for the injection kicker was improved. While the rise-time of 195 nsec was achieved, new reflection peak which induces the additional injection beam loss was appeared. A new small kicker will be developed to compensate the single kick by the residual field for the higher intensity operation.

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