# REDUCTION OF THE KICKER IMPEDANCE MAINTAINING THE PERFORMANCE OF PRESENT KICKER MAGNET AT RCS IN J-PARC

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## Abstract

The present four-terminal kicker at the Rapid Cycling Synchrotron (RCS) at the Japan Proton Accelerator Research Complex (J-PARC) has the power-saving benefit due to the doubled excitation currents by shorting two-terminals. On the other hand, beam instabilities are excited by the kicker impedances. In this report, we describe a scheme to reduce the kicker impedances using diodes (nonlinear devices) with resistors, while retaining the benefit of the doubled kicker excitation currents.

## INTRODUCTION

The RCS at J-PARC [1] aims to achieve a megawatt-class beam. When two bunched beams, each containing $4.15 \times 10^{13}$ particles per bunch, are accelerated from 400 MeV to 3 GeV at a repetition rate of 25 Hz, a 1-MW beam can be performed at the RCS.

The beam instability [2] excited by the kicker, is a major limiting factor in producing high intensity, small emittance beams [3, 4]. The objective of this report is reducing the kicker impedance [5, 6], while maintaining the performance of present kicker to extract 3-GeV beams from the RCS [7].

## BASIC CONCEPT TO MODIFY THE PRESENT KICKER

The kicker at the RCS consists of a Pulse-Forming-Line (PFL), a thyratron and a magnet [7]. The magnet has four terminals. Two are connected to 130-m-long coaxial cables. The other two are shorted with plates, which creates doubled excitation currents, due to the superposition of the forward and reflection currents, when beams are extracted from the RCS [7]. The ends of the cables connecting to the PFL are completely open during the acceleration of a beam. Hence, the shorting plates create a resonance structure in the kicker impedance [6], which restricts a tunable parameter region for high intensity beam operations [8, 9].

The spiky structures of the impedance are created by the reflection of beam-induced currents into the cables [6]. Thus, the kicker impedance can be reduced by inserting resistors somewhere around the terminals at the kicker magnet [10, 11]. However, if we simply adopt this scheme for the present kicker, the merit of the doubled excitation currents is wasted, due to the inserted resistors.

Instead, let us consider the different scheme shown in Fig. 1, in which diodes and resistors are inserted between the PFL and 130 m coaxial cables. The diodes isolate the

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Figure 1: A schematic illustration of the modified kicker in terms of electric circuit.

resistors from the PFL, but, the resistors can still be seen by a beam.

## PULSE CURRENT FORMATION FOR BEAM EXTRACTIONS

Table 1: SPICE Parameters for one module, of which the diode in Fig. 1 consists.

| | |
|---|---|
| is : Saturation current | 2.04E-06 [A] |
| rs : Ohmic resistance | 0.01 [Ω] |
| n : Emission coefficient | 8.28 |
| tt : Transit time | 7.21E-04 [s] |
| cjo : Zero-bias junction capacitance | 1.52E-09 [F] |
| vj : Junction Potential | 0.423 [V] |
| m : Grading coefficient | 0.063 |
| eg : Action Energy | 1.1 [eV] |
| xti : Saturation current Temperature exponent | 3 |
| kf : Flicker noise coefficient | 0 |
| af : Flicker noise exponent | 1 |
| fc : Coefficient for forward-bias | 0.5 |
| bv : Reverse breakdown voltage | 4000 [V] |
| ibv : Current at breakdown voltage | 5.00E-05 [A] |
| tnom : Normal temperature | 25 [°C] |

The diode must have a sufficiently high reverse voltage $V_R$ to block the DC current from the PFL and a low forward voltage $V_F$ so that the beams can see the resistors. At the RCS, $V_R$ must be 40 kV or higher, while $V_F$ should be 50V or lower. The diode consists of 13 modules in 4 parallel. Table 1 represents SPICE (Simulation Program with Integrated Circuit Emphasis) parameters for one module [12]. From here on, let us call the electric element, consisted of the diodes and the resistors, the diode unit (see the magnified figure in Fig. 1).

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In Fig. 1, let us switch on the PFL, and monitor the currents at the position A, one of which the divided forward current is delivered into, and at the kicker magnet. Figure 2 shows the simulation results by using the SPICE code. The left and right figures show the currents at the position A and at the kicker magnet, respectively. The red and blue lines show the results with and without the diode unit, respectively. The first and second trapezoidal waveforms in the left figure represent the forward current from the PFL and the reflection current from the kicker magnet, respectively. The insertion of diode unit creates the impedance mismatch for the reflection current, by which the current (red) is enhanced compared to the blue one.

The simulation result shown in the right figure of Fig. 2 seems to ensure that the excited current at the kicker is doubled compared to the total forward current, and that both the red and the blue lines are almost identical in the flat top.
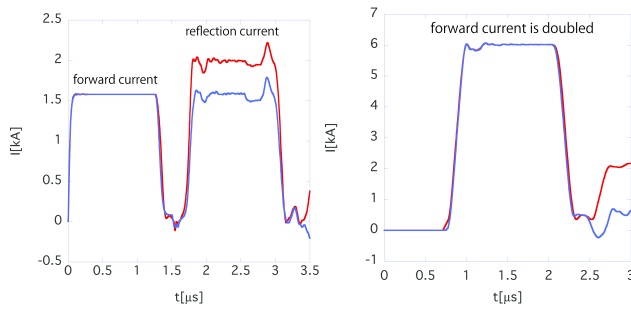


Figure 2: SPICE-simulation results of the currents at the position A (left) and at the kicker magnet (right) in Fig. 1.

From an experimental point of view, one concern is whether the durability of diode is sufficient when the beam-extraction current flows, and what a degree the diode unit affects on the current waveform, though the result (right) in Fig. 2 suggests no significant deformation on the waveform.

Now, let us measure both the currents at the positions A and B in Fig. 1. The measured results are shown in Fig. 3. The red and blue lines show the results with and without the diode unit, respectively. The right figure illustrates that almost no current flows on the diode during the passage of forward current except the rising and falling periods. The result demonstrates that the diode is sufficiently durable, as expected. A part of the reflection current flows the diode and is finally consumed at the resistors.

On the other hand, the left figure in Fig. 3 reveals that the oscillation occurs (red) on the forward current during the rising period due to the diode unit, since no oscillation exists on the blue one. The magnified figure of the pulse rising edge is shown in the left figure of Fig. 4, as well.

The oscillation is due to the present measurement-setup, where the diodes and resistors are set inside the container, shown in Fig. 1, which is connected to the thyratron through 3.1-m long 20 Ω coaxial cable. The container and the cable may create significant additional inductances and capacitances and deform the current waveform.
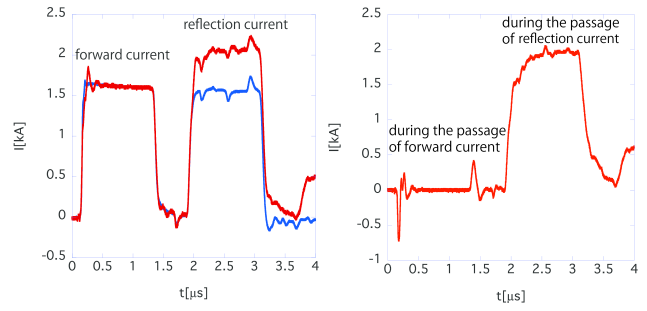


Figure 3: Measurements of the current at the position A (left) and at B (right) in Fig. 1.
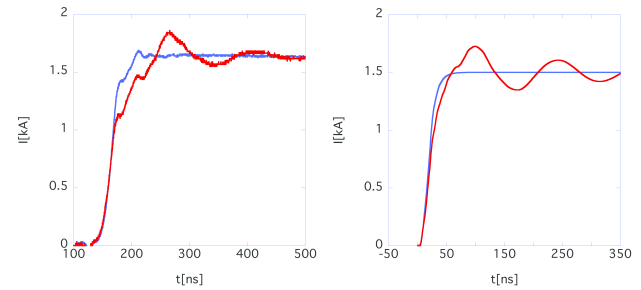


Figure 4: Magnified figure of the left figure of Fig. 3 (left) around the pulse rising edge of forward current and the 3-D simulation result (right) by using the CST code.

In order to estimate the effect, let us execute a three-dimensional (3-D) simulation, whose result is shown in the right figure of Fig. 4, with the CST code [13]. The simulation result matches well with the experimental result (left).
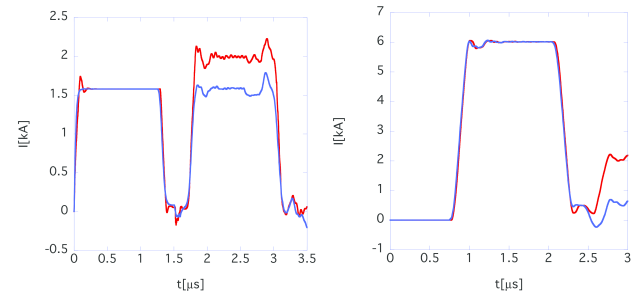


Figure 5: SPICE-simulation results of the current at the position A (left) and the excited current at kicker magnet (right) in Fig. 1.

In addition, we calculate the $S$-matrix of container with the CST code. Finally, the impedance of the container is well approximated as four parallel resonator circuits, which are specified as ($R_1$= 296 Ω, $L_1$= 166.5 nH, $C_1$=25.3 pF), ($R_2$= 1286 Ω, $L_2$= 26.8 nH, $C_2$=41.4 pF), ($R_3$= 9799 Ω, $L_3$= 10.9 nH, $C_3$=8.12 pF), and ($R_4$= 223.5 Ω, $L_4$= 2.65 nH, $C_4$=39.6 pF). After incorporating the parameters into the SPICE code, let us recalculate the currents at the position A

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and at the kicker in Fig. 1. Figure 5 shows the results. The left figure successfully reproduces the left figure of Fig. 3 (measurements). Hence, we conclude that the impedances of coaxial cable and container deform the current waveform.
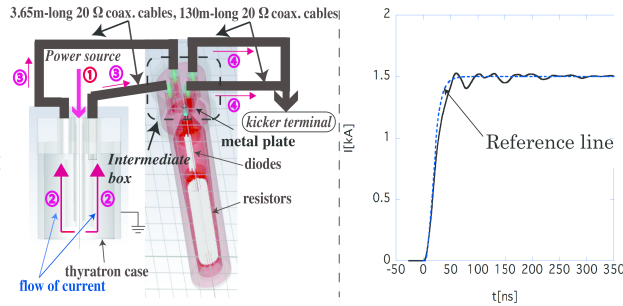


Figure 6: A schematic of simulation model (left), by which examines the effect of intermediate box on the pulse current rising edge (right).

As shown in the right figure of Fig. 5, though the oscillation does not seem to significantly deform the current at kicker, let us propose some measures to suppress the oscillation. One measure is shortening the cable length from 3.1 m to 1m, which may be mechanically difficult to be made.

Another measure is introducing an intermediate grounded box, as shown in the left figure of Fig. 6. The box has four ports for 20 Ω coaxial cables, whose inner conductors are connected on a metal plate in the box. The 3.1 m coaxial cable is removed by directly connecting the plate to the diode unit. The 3-D simulation result is shown in the right figure of Fig. 6. Hence, the scheme expects to suppress the oscillation on the waveform (refer to Fig. 4).

## REDUCTION OF THE IMPEDANCE

The reference [14] copes with ways of finding whether the kicker impedances are reduced with this new scheme by both measurements and simulations. By observing the beam-induced voltage and current on the diode unit, the impedance can be measured, which demonstrated that the impedance was decreased experimentally [6, 10, 11, 14].

From a simulation point of view, since 130-m-long cables, whose ends are terminated with nonlinear devices, i.e. diodes, and resistors, are connected to the kicker, it is almost impossible to carry out 3-D simulation with the Wake Solver of CST code, because excessive memory and CPU time must be secured for such long cables.

In order to overcome this difficulty, we introduced an experimental aspect into simulations. A typical way of measuring impedances is observing the $S$-matrix of the coaxial structure made by stretching wires inside the device under test (kicker), before converting it into the impedance by the standard log-formula [15]. In this setup, the effect of cables can be easily incorporated into simulations by the MicroWave Solver, bypassing the Wake Solver, of CST.

For given pulsed currents on the wires (simulating the beams in the kicker), we calculated all voltages and currents

in time domain, then transformed them into those in frequency domain. Figure 7 shows the simulation results [14]. The green, black, blue and red lines represent the results for 300 kW-eq, 500 kW-eq, 750 kW-eq and 1 MW-eq beam powers, respectively. The results illustrate that the kicker impedances decrease, as the beam intensity increases. This is because as the current on wire increases, the V-I curve of diode rises quickly, which means the diode becomes more conductive and the impedance matching condition is more satisfied toward higher intensity beams.
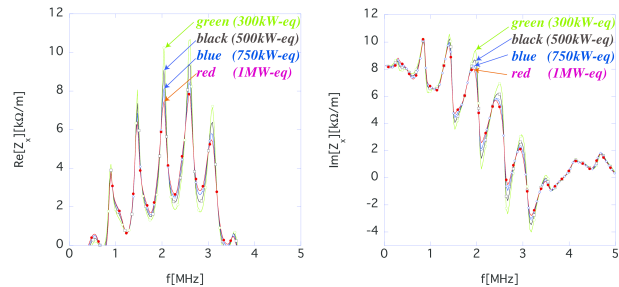


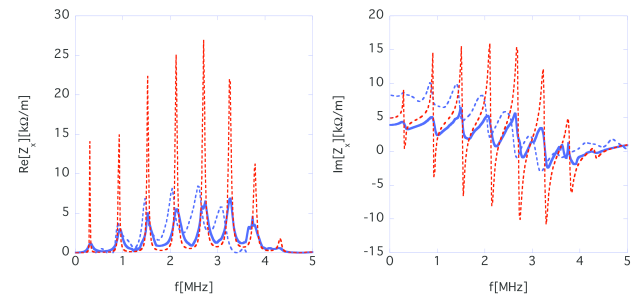Figure 7: Simulation results for the kicker impedance.



Figure 8: Analytical result, simulation one, and measurement for the kicker impedance.

Figure 8 summarizes measurement (blue solid) [11, 14] and simulation (blue dashed) results for $3.11 \times 10^{13}$ (750 kW-eq) particles per bunch when the cable terminals are terminated by the diode unit, and the analytical (red) results for the present kicker [6]. The impedance of present kicker is significantly reduced by the diode unit. The agreement between the blue solid and blue dashed lines is relatively good. Finally, the measurements demonstrate that the simulation technique [14, 16] can provide a guideline to estimate the impedances of the kicker magnet connected to the 130-m-long coaxial cables terminated with the diode unit.

## SUMMARY

We have developed a scheme to reduce the kicker impedance at the RCS at J-PARC, sustaining the kicker function of beam extraction. The diode unit is inserted between the ends of the coaxial cables and the PFL. The unit ensures doubled excitation currents for beam extraction from the superposition of the forward and reflection currents, reducing the kicker impedance.

# REFERENCES

[1] J-PARC, http://j-parc.jp/index-e.html

[2] A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*, Wiley, New York, 1993.

[3] Y. Shobuda *et al.*, "Theoretical elucidation of space charge effects on the coupled-bunch instability at the 3 GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex", Prog. Theor. Exp. Phys., **2017**, 1, 013G01, (2017), https://doi.org/10.1093/ptep/ptw169

[4] P. K. Saha *et al.*, "Simulation, measurement, and mitigation of beam instability caused by the kicker impedance in the 3-GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex", Phys. Rev. Accel. Beams **21**, 024203, (2018), https://doi.org/10.1103/PhysRevAccelBeams.21.024203

[5] Y. Shobuda, Y. Irie and T. Toyama, "Analytical approach to evaluate coupling impedances of traveling kicker magnets", Nuclear Instruments and Methods in Physics Research A, **691**, 135, (2012), https://doi.org/10.1016/j.nima.2012.06.066

[6] Y. Shobuda, Y. Irie, T. Toyama, J. Kamiya and M. Watanabe, "Measurement scheme of kicker impedances via beam-induced voltages of coaxial cables", Nuclear Instruments and Methods in Physics Research A, **713**, 52, (2013), https://doi.org/10.1016/j.nima.2013.02.037

[7] J. Kamiya, T. Takayanagi, and M. Watanabe, "Performance of extraction kicker magnet in a rapid cycling synchrotron", Phys. Rev. ST Accel. Beams **12**, 072401, (2009), https://doi.org/10.1103/PhysRevSTAB.12.072401

[8] Y. Shobuda *et al.*, "Coupled bunch instability and its cure at J-PARC RCS", in Proc. IPAC'17, Copenhagen, Denmark, p. 2946, (2017), https://doi.org/10.18429/JACoW-IPAC2017-WEPIK014

[9] H. Hotchi *et al.*, "Realizing a high-intensity low-emittance beam in the J-PARC 3-GeV RCS, Journal of Physics: Conference Series, **874**, 012059 (2017), https://doi.org/10.1088/1742-6596/874/1/012059

[10] Y. Shobuda, N. Hayashi, T. Takayanagi, Y. Toyama, and Y. Irie, "A trial to reduce the kicker impedance of 3-GeV RCS in J-PARC", Proc. of IPAC'13, Shanghai, China, p. 1742, (2013), http://accelconf.web.cern.ch/accelconf/IPAC2013/papers/tupwa010.pdf

[11] Y. Shobuda *et al.*, "The kicker impedance and its effect on the RCS in J-PARC", in Proc. HB'14, Michigan, USA, p. 369, (2014)

[12] http://www.origin.co.jp/

[13] CST STUDIO SUITE, https://www.cst.com.

[14] Y. Shobuda *et al.*, "A scheme to reduce the beam-impedance of the kicker at the 3-GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex", submitted to Phys. Rev. AB.

[15] A. W. Chao and M. Tigner, eds, Handbook of Accelerator Physics and Engineering, Wiley (1999).

[16] Y. Shobuda and Y. H. Chin, "Resistive-wall impedances of a thin neg coating on a conductive chamber", Prog. Theor. Exp. Phys., **2017**, 12, 123G01, (2017), https://doi.org/10.1093/ptep/ptx167