Impedance measurements of the extraction kicker system for the rapid cycling synchrotron of China Spallation Neutron Source*

Liang-Sheng Huang (黄良生)[1,2] Sheng Wang(王生)[1,2] Yu-Dong Liu(刘瑜冬)[1,2;1)]
Yong Li(李勇)[1,2] Ren-Hong Liu(刘仁洪)[3] Ou-Zheng Xiao(肖欧正)[3]

[1] Dongguan Campus, Institute of High Energy Physics (IHEP), Chinese Academy of Sciences (CAS), Dongguan 523803, China
[2] Dongguan Institute of Neutron Science (DINS), Dongguan 523808, China
[3] Institute of High Energy Physics, Chinese Academy of Science, Beijing 100049, China

Abstract: The fast extraction kicker system is one of the most important accelerator components and the main source of impedance in the Rapid Cycling Synchrotron of the China Spallation Neutron Source. It is necessary to understand the kicker impedance before its installation into the tunnel. Conventional and improved wire methods are employed in the impedance measurement. The experimental results for the kicker impedance are explained by comparison with simulation using CST PARTICLE STUDIO. The simulation and measurement results confirm that the window-frame ferrite geometry and the end plate are the important structures causing coupling impedance. It is proved in the measurements that the mismatching from the power form network to the kicker leads to a serious oscillation sideband of the longitudinal and vertical impedance and the oscillation can be reduced by ferrite absorbing material.

Keywords: CSNS, RCS, impedance measurement, extraction kicker, mismatching, oscillation

PACS: 29.27.Bd **DOI:** 10.1088/1674-1137/40/4/047002

1 Introduction

The driving terms of beam instabilities in an accelerator depend on the interaction between the charged particles and the surroundings and are usually described by coupling impedance. The longitudinal coupling impedance may lead to beam energy loss and thus heating of components and beam energy spread [1]. The transverse impedance contributes to the instability when the off-axis beam passes through vacuum components. For an accelerator project with high intensity and high luminosity, careful establishment of an "impedance budget" is a prerequisite for its normal performance. Therefore, theoretical analyses, simulations and measurement on the bench are crucial tasks for the accelerator design, development, and research. The analytical formulas of some vacuum components are given in references [2-4], and some developed codes are used to simulate the coupling impedance, such as ABCI, HFSS [5] and CST PARTICLE STUDIO [6], but the impedances of some complicated components are difficult to estimation by analytical formula and simulation, so impedance measurement on the bench is useful at that time.

The conventional wire-method has been widely employed in coupling impedance measurement on the bench, including the coaxial-wire method for longitudinal impedance and the twin-wire method for transverse impedance. Longitudinal coupling impedance measurement with the coaxial wire method was first achieved by A. Faltens in 1971 [7]. M. Sands and J. Rees performed coupling impedance measurement in the time domain [8]. With the development of technique, impedance measurement in the frequency domain is now widely used. The loop method, which is the origin of the twin-wire method, was first implemented for transverse impedance measurement by G. Nassibian in 1978 [9]. L. Walling measured the transverse impedance by the twin-wire method in 1987 and gave the formula of distributed component impedance, the logarithmic formula [10]. F. Caspers and H. Hahn gave some useful and comprehensive documents for impedance measurement on the bench [11,12]. Moreover, H. Hahn showed its validity for longitudinal impedance measurement with coaxial-wire [13]. With improvements in accuracy in both theory and technique, the wire method has become the standard method for impedance measurement. In addition, the longitudinal impedance is also measured by the twin-wire [14], so it

Received 29 June 2015, Revised 21 September 2015
* Supported by National Natural Science Foundation of China (11175193, 11275221)
1) E-mail: liuyd@ihep.ac.cn

is convenient to measure the longitudinal and transverse impedance at the same time. Some methods and examples of impedance measurement are shown in references [15−20].

The accelerator system in the China Spallation Neutron Source (CSNS) consists of an H^- linac, a proton Rapid Cycling Synchrotron (RCS), and two beam transport lines [21]. The RCS is designed to accelerate the proton beam from 80 MeV to 1.6 GeV with a repetition rate of 25 Hz. The beam power of the CSNS is 100 kW, and it will be upgraded to 500 kW. The bunch length in RCS is shortened from 420 ns to 80 ns. The frequency range of interest to the RCS covers frequencies from ∼100 MHz down to below 1 MHz, with emphasis on the 1−12 MHz range. Due to the high beam intensity and high repetition rate, the beam loss must be controlled to a very low level. In the case of the RCS, the complicated extraction kicker is the most critical component devoted to the impedance [22], so it should be measured on the bench. The coaxial-wire method is used to measure the longitudinal coupling impedance. The transverse coupling impedance is first measured by the twin-wire method, and then, one wire loop is used to measure the transverse impedance at low frequency.

In this paper, the kicker system is introduced in Section 2, then its longitudinal and transverse impedance measurements are presented in Section 3 and Section 4, respectively. In the last section, the impedance measurement result is summarized and discussed.

2 The extraction kicker system

The parameters of the kicker magnet are shown in Table 1 [23, 24]. A schematic view of the kicker system is shown in Fig. 1, and the main proportion of the kicker magnet is the window-frame geometry ferrite made of CMD5005 material, as shown in Fig. 2. The side strap in Fig. 1 connects the upper and lower busbar plates. The busbar and the window-frame ferrite are located in a vacuum vessel, which is about 0.58 m in length. The busbar is fully isolated from the vessel by the ceramic block in feedthrough. The total inductance of the kicker is about 0.9 μH and its capacitance, mainly from the end plate, is about 30 pF. The eddy current strip (ECS) located in the vertical center of the ferrite block is employed to reduces the longitudinal impedance.

For the beam extraction, the pulse form network (PFN) connects the kicker with the 130 m length cable [25]. The characteristic impedance of the cable is 12.5 Ω, and the impedance of the PFN is 6.25 Ω. The cable parallels with the 12.5 Ω termination and matches the PFN. Moreover, the PFN is cut off by the saturated reactor when the beam ramps; at that time, the cable connects on the termination, and it matches. In fact, there is some mismatching between the cable, termination and the PFN [17, 26], which may cause longitudinal and vertical impedance. Therefore, the measurements were done with different connection conditions: the kicker magnet without the long cable, the PFN and the termination (kicker magnet) and the kicker magnet connecting on the cable, the PFN and the termination (kicker system).

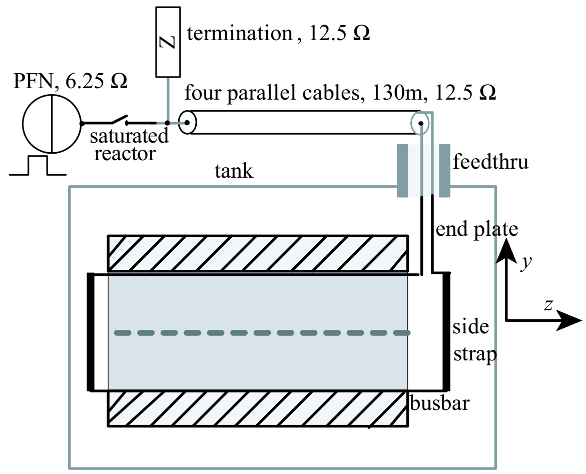

Fig. 1. Schematic view of the CSNS/RCS kicker system.

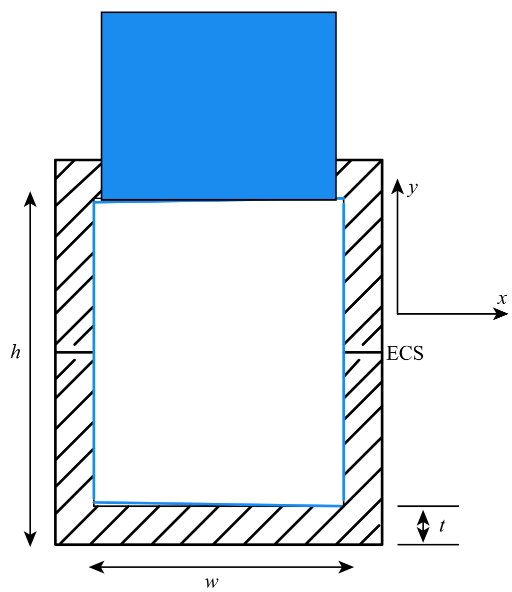

Fig. 2. (color online) Schematic view of the window-frame geometry.

Table 1. Parameters of the kicker magnet.

strength/T	angle/mrad	length/m	top time/ns	width/mm	gap/mm	rise time/ns
0.0558	2.6	0.4	>550	155	136	⩽250

3 Longitudinal impedance measurement

The standard method of longitudinal measurement on the bench is coaxial-wire, in which wire is inserted on-axis into the Device Under Test (DUT) to measure the longitudinal impedance. The kicker with a thin copper wire on-axis can be regarded as a two-port microwave circuit, of which the forward scattering coefficient can be measured with a Vector Network Analyzer (VNA). The schematic setup of the coaxial-wire method is shown in Fig. 3. The longitudinal coupling impedance can be obtained by measuring the forward scattering coefficient, S_{21}, of the DUT and a smooth reference beam pipe of equal length (REF) as [10]

$$Z=-2R_{\rm c}\ln\left(\frac{S_{21,\,\rm DUT}}{S_{21,\,\rm REF}}\right), \quad (1)$$

where $S_{21,\rm DUT}$ and $S_{21,\rm REF}$ are the forward scattering coefficients of the DUT and the REF, respectively. $R_{\rm c}$ is the characteristic impedance formed by the reference pipe with the copper wire as a coaxial transmission line structure. The radius of the beam pipe and inserted wire are 125 mm and 0.25 mm, respectively. Impedance matching between the VNA (50 Ω) to the reference plane ($R_{\rm c}\sim 372$ Ω) is achieved by connecting a series resistor ($R_{\rm s}\sim 320$ Ω) at each port of the line. The matching resistor is mounted into the SUCOBOX which is 35 mm long [27].

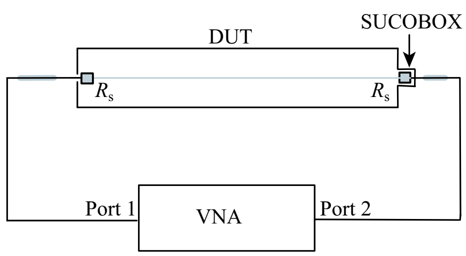

Fig. 3. Schematic setup of the longitudinal coupling impedance measurement.

The longitudinal coupling impedance of the kicker magnet and the kicker system are obtained and shown in Fig. 4 and Fig. 5, respectively. The average longitudinal impedance of the kicker is about 7+j6.5 Ω, which is very weak for the RCS beam. The impedance peaks with frequency 18 MHz and 30 MHz from the end plate and the window-frame ferrite geometry, respectively. The peak at 18 MHz disappears in Fig. 5 when the kicker magnet connects on the cable, the PFN and the termination.

For the impedance of the kicker system, it is clear to see that an oscillation appears in Fig. 5. The frequency spacing of the oscillation is 0.72 MHz. Moreover, the spacing of the reflection wave from the long cable can be expressed theoretically as

$$\Delta f=\frac{c}{2\alpha L}, \quad (2)$$

where, L is the length of the cable. The refractive index of the cable medium, α, is 1.6 for polythene. The spacing is 0.72 MHz, which is consistent with the result of the measurement. It matches perfectly at low frequency and the oscillation sideband is invisible, which is the characteristic of the distribution effect of the termination. Therefore, it is certain that the oscillation comes from mismatching from the PFN to the kicker magnet.

To prove the validity of the measured longitudinal impedance, the kicker impedance is simulated by CST PARTICLE STUDIO [6]. Due to excessive memory consumption and CPU time, the simulation only models the structure of the kicker magnets. The comparison between simulation and experiment results are displayed in Fig. 4, which confirms the reliability of the measurement.

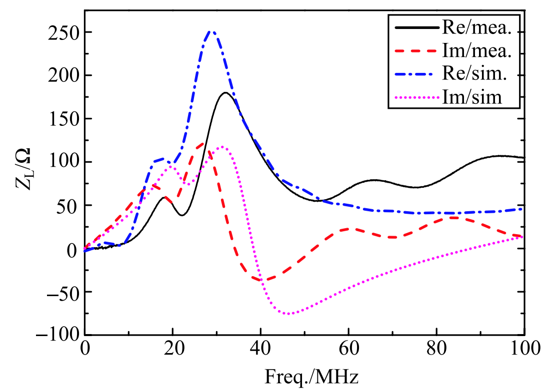

Fig. 4. (color online) Longitudinal coupling impedance of the kicker magnet.

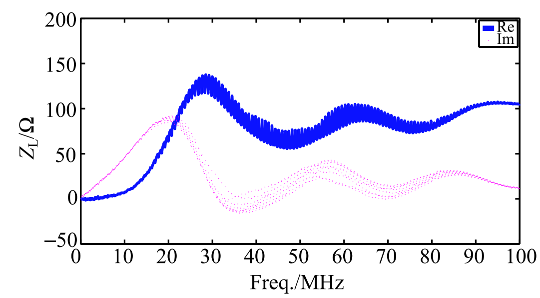

Fig. 5. (color online) Longitudinal coupling impedance of the kicker system.

To reduce the oscillation caused by mismatching between the PFN and kicker magnet, a ferrite absorbing ring of type 8C12 [28, 29] is placed around the feedthrough and the absorption effect is shown in Fig. 6.

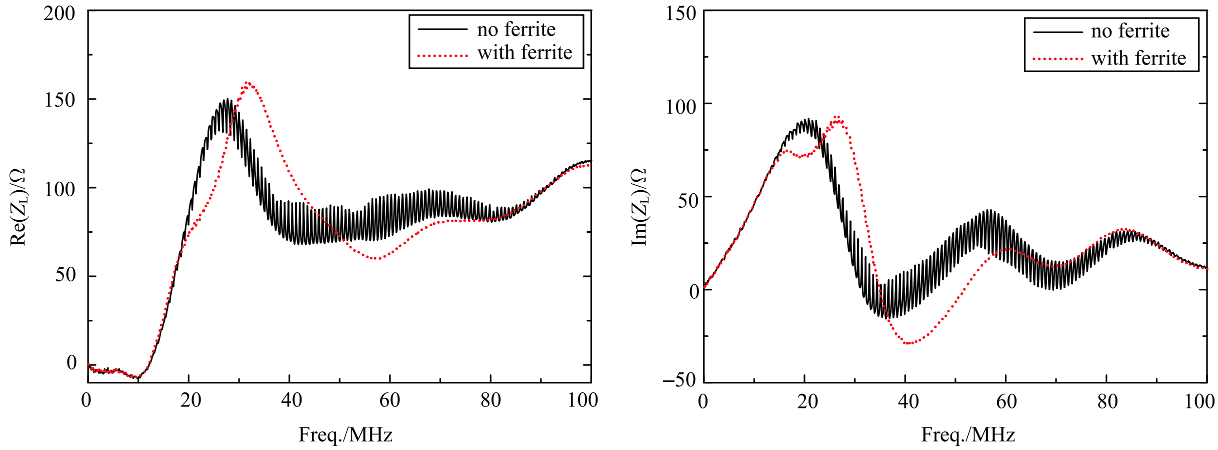

Fig. 6. (color online) Longitudinal impedance of the kicker with and without the ferrite ring.

4 Transverse impedance measurement

For transverse impedance measurements, the standard way is to insert two parallel wires with out-of-phase signal (differential-mode) through the DUT to produce a dipole current moment; this is called the twin-wire method. The forward scattering coefficient, S_{21}, is measured. A schematic view of the measurement is shown in Fig. 7. The spacing ($2d$) of the copper wire with 0.5 mm diameter is 40 mm, and the characteristic impedance of the twin-wire (R_c) is 603 Ω [30], thus a 250 Ω resistor ($R_s/2$) is used for matching. The differential-mode signal is offered by the hybrid - ZFSCJ-2-1 [31] and its isolation is bigger than 30 dB. Four 6 dB attenuators between the hybrid and the DUT are involved in the reflection from the port.

The transverse coupling impedance of the kicker can be obtained with the scattering coefficients $S_{21,\mathrm{DUT}}$ and $S_{21,\mathrm{REF}}$ as

$$Z=-2\frac{c}{\omega(2d)^2}R_c\ln\left(\frac{S_{21,\mathrm{DUT}}}{S_{21,\mathrm{REF}}}\right), \tag{3}$$

with angular frequency ω.

The vertical coupling impedance with frequency range from 10 MHz to 100 MHz is displayed in Fig. 8. It is clear that there is an impedance peak of the kicker magnet at about 18 MHz from the window-frame ferrite geometry and the end plate, but it disappears in the measurement of the kicker system. Moreover, the oscillation with frequency spacing about 0.72 MHz from mismatching between cable and power supply also appears in the measurements of the kicker system.

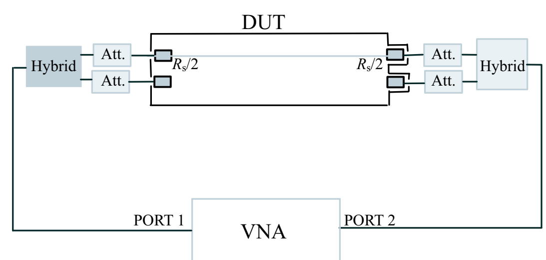

Fig. 7. Schematic view of transverse impedance measurement by the twin-wire.

Due to serious measurement errors with the twin-wire method in the lower frequency range such as 10 MHz [32], one wire loop is adopted for that range. A schematic view of the loop is shown in Fig. 9. With the measured input impedances for DUT and REF, the transverse impedance can be expressed as [33]

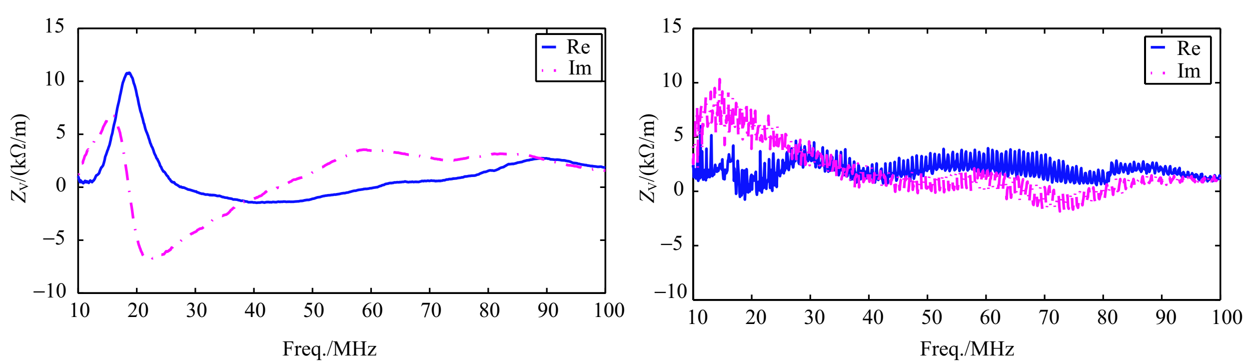

Fig. 8. (color online) Vertical impedance of the kicker magnet (left) and the kicker system (right).

$$Z_{\mathrm{T}}=\frac{c}{\omega}\frac{Z^{\mathrm{DUT}}-Z^{\mathrm{REF}}}{(2d)^{2}}, \tag{4}$$

with the input impedance of the DUT, Z^{DUT}, and the REF, Z^{REF}.

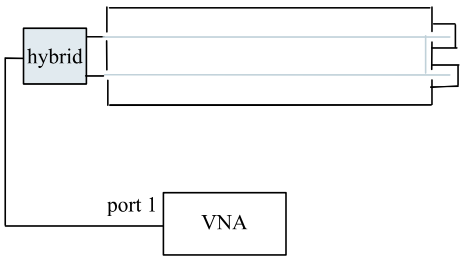

Fig. 9. Schematic setup of the transverse impedance measurement with the loop.

The measured horizontal impedance for the kicker system with the loop method is similar to the pure kicker magnet shown in Fig. 10, so the horizontal coupling impedance is mostly not affected by the cable, the PFN and the termination.

The vertical impedance results for the kicker magnet and kicker system are shown in Fig. 11. The impedance peak positioned at 18 MHz agrees well with the result from the twin-wire method in Fig. 8, and it is also depressed for the kicker system. Similarly, the oscillation with frequency about 0.72 MHz from reflection of mismatching is shown when the kicker connects on the cable, PFN and termination.

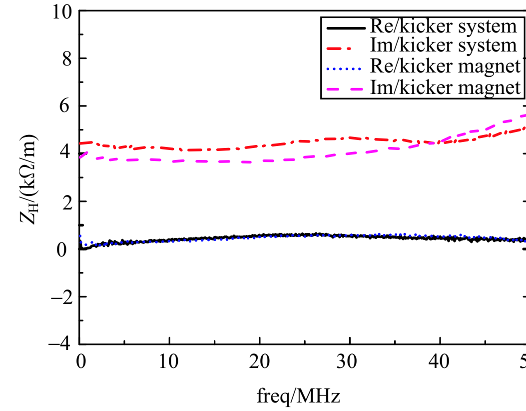

Fig. 10. (color online) Measured horizontal impedance of the kicker by loop.

Further measurements of reflection for the kicker magnet only connecting with the long cable (cable open) are shown in Fig. 12. It is clear that the start frequency

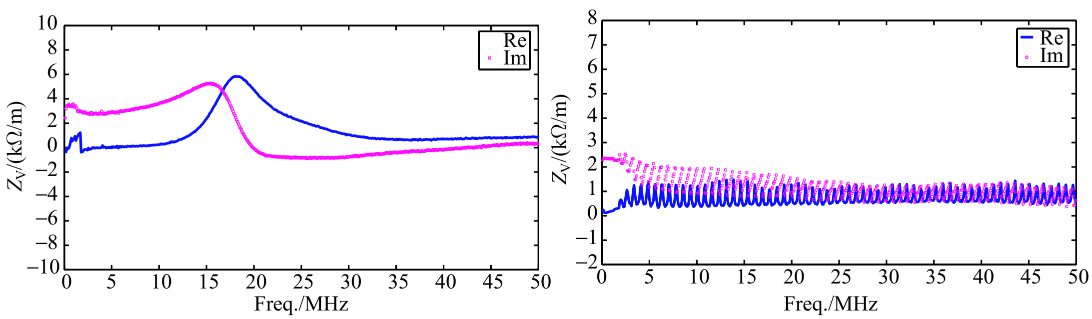

Fig. 11. (color online) Measured vertical impedance of the kicker magnet (left) and the kicker system (right) by loop.

of this oscillation in Fig. 13 is about 0.35 MHz, which agrees with the theoretical estimation with the following formula: the start of the oscillation is expressed theoretically as

$$f_{\mathrm{start}}=\frac{c}{4\alpha L}. \tag{5}$$

This confirms the assumption that the oscillation comes from the mismatching from the PFN to the kicker.

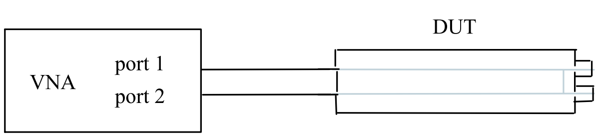

Fig. 12. Improved loop method for transverse impedance measurement.

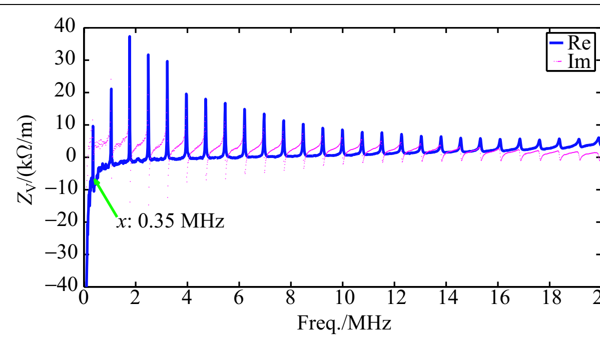

Fig. 13. (color online) Vertical impedance of the kicker with the cable open.

The experimental results are also verified by simulation with CST PARTICLE STUDIO as shown in Fig. 14.

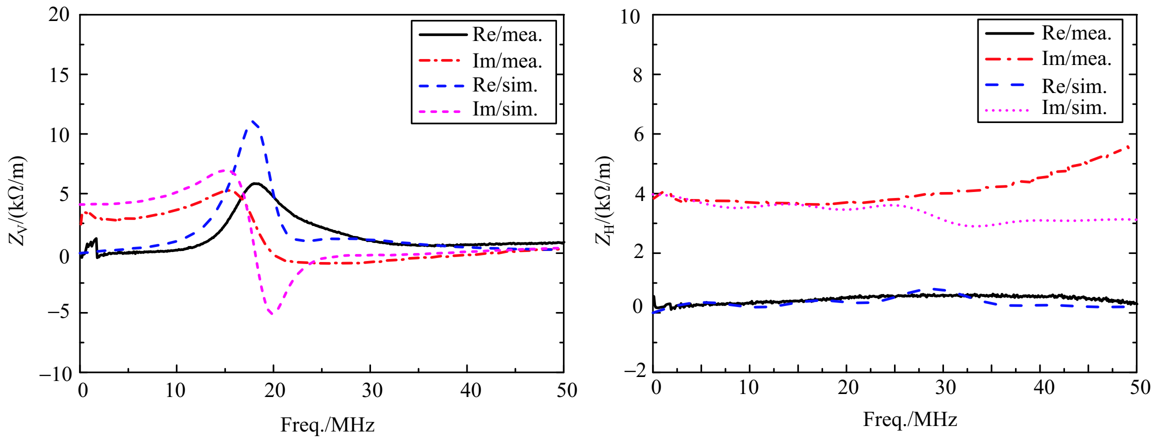

Fig. 14. (color online) Simulated and measured transverse impedance of kicker magnet.

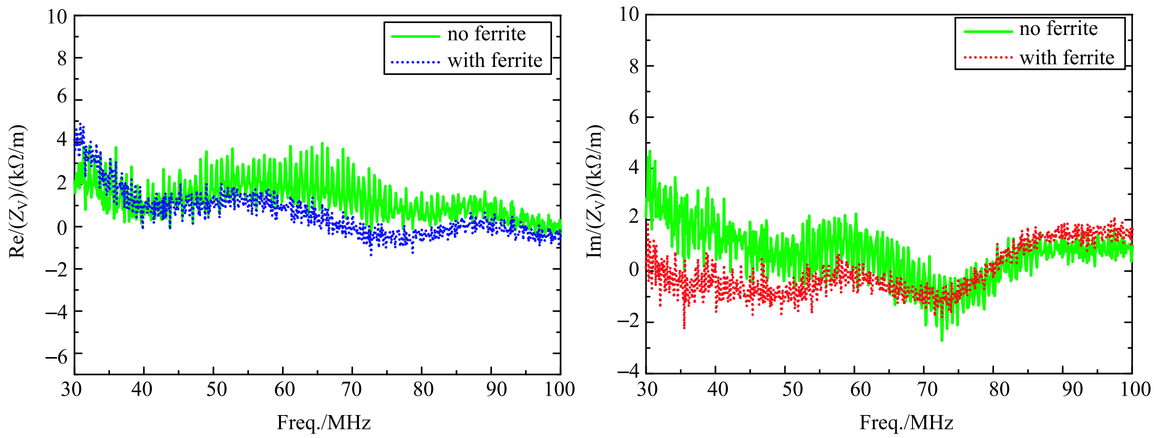

Fig. 15. (color online) Vertical impedance of the kicker system with and without the ferrite ring.

It is obvious that the difference in transverse impedance between measurements and simulation is small, so the measured impedance is reliable.

The absorption of signal oscillation by covering the feedthrough with 8C12 ferrite ring is shown in Fig. 15.

5 Summary

The longitudinal and transverse coupling impedances of the fast extraction kicker in CSNS/RCS have been measured. The measured impedances of the kicker magnet are explained by comparison with simulation using CST PARTICLE STUDIO, and the results agree well. The average longitudinal impedance of the kicker system is about 7+j6.5 Ω, and the vertical and horizontal impedance are 1.2+j2.7 kΩ/m and 0.4+j4.5 kΩ/m, respectively. The simulation and the measurement indicate that the window-frame ferrite geometry and the end plate are most important structures causing the coupling impedance. The mismatching between PFN and kicker magnet may have some negative effects on beam stability, and absorbing substances such as a ferrite ring can be adopted to suppress this reflection.

We would like to acknowledge the support of many colleagues.The authors would also like to thank Prof. Yoshiro Irie and Prof. Fritz Caspers for many discussions and comments in the measurement.

References

1 A. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerator* (New York: Wiley Publishing Company, 1993), p. 81-174
2 B. W. Zotter et al, *Impedances and Wakes in High-Energy Particle Accelerators* (Singapore: World Scientific, 1998), p.73
3 S. Y. Lee, *Accelerator Physics* (Singapore: World Scientific, 2004), p. 216, 369
4 A. Chao and M. Tigner, *Handbook of Accelerator Physics and Engineering* (Singapore: World Scientific, 1998), p. 194
5 http://www.ansys.com, retrieved 25th Nov. 2014
6 http://www.cst.com, retrieved 21th Nov. 2014
7 A. Faltens et al, An Analog Method for Measuring the Longitudinal Coupling Impedance of a Relativistic Particle Beam with Its Environment, in *Proc. of the 8th International Conference on High-Energy Accelerators* (1971), p. 338
8 M. Sands and J. Rees, A Bench Measurement of the Energy Loss of a Stored Beam to a Cavity, PEP report, PEP-95, 1974
9 G. Nassibian et al, Nucl. Instrum, Methods A, **159**: 21–27 (1979)
10 L. S. Walling et al, Nucl. Instrum, Methods A, **281**: 433 (1989)
11 F. Caspers, Bench Methods for Beam-coupling Impedance Measurement, CERN–report, CERN PS/88-59. 1988
12 H. Hahn and F. Pedersen, On Coaxial Wire Measurement of the Longitudinal Coupling Impedance, BNL-report, 50870, 1978
13 H. Hahn, PRST-AB, **3**: 122001 (2000)
14 T. Toyama et al, Coupling Impedance of the J-PARC Kicker Magnets, in *Proc. of HB*2006 (2006), p. 140
15 H. Gang et al, Longitudinal Broadband Impedance Measurement System by Coaxial Line Methods, in *Proc. of the PAC'*01 (2001), p. 2060
16 H. Hahn et al, Measured Transverse Coupling Impedance of RHIC Injection and Abort Kickers, in *Proc. of the PAC'*01 (2001), p. 1829
17 H. Hahn, PRST-AB, **7**: 103501 (2004)
18 B. Podobedov et al, PRST-AB, **9**: 054401 (2006)
19 Y. Shobuda et al, Horizontal Impedance of the Kicker Magnet of RCS at J-PARC, in *Proc. of IPAC'*10 (2010), p. 2024
20 B. Salvant, Impedance *Model of the CERN SPS and Aspects of LHC Single-Bunch Stability*, Ph. D Thesis (CERN, 2010)
21 S. Wang et al, Scientific China Physics M & A, **54**: 239 (2011)
22 Y. Liu, High Power Laser and Particle Beams, **25** (2): 465 (2013)(in Chinese)
23 J. Y. Tang et al, Extraction System Design for the CSNS/RCS, in *Proc. of EPAC'*06 (2006), p. 1777
24 W. Kang et al, IEEE Trans. on App. Sup., **20** (3): 356 (2010)
25 Y. Chi et al, Chin. Phys. C, **32** (Z1): 25 (2008)
26 Y. Shobuda et al, Nucl. Instrum, Methods A, **713**: 52 (2013)
27 http://de.farnell.com/huber-suhner/fbb-cb-50-0-1-e/sucobox-prototy-box/dp/4162950, retrieved 15th Nov. 2013
28 F. Caspers, private contact, Oct. 2013
29 http://www.ferroxcube.com/FerroxcubeCorporateReception/datasheet/FXC_HB2013.pdf, retrieved 16th Feb. 2014
30 A.W. Gent, Electrical Comm., **33**: 234 (1956)
31 http://www.minicircuits.com, retrieved 17th Nov. 2013
32 H. Hahn, Direct Transverse Coupling Impedance Measurements of Kicker Magnets, BNL/SNS TECHNICAL NOTE, 120, 2003
33 A. Mostacci et al, Bench Measurements of Low Frequency Transverse Impedance, in *Proc. of the PAC'*03 (2003), p. 1801