COUPLING IMPEDANCE MEASUREMENTS OF THE EXTRACTION KICKER IN CSNS/RCS*

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Abstract

The fast extraction kickers are the main source of impedance in China Spallation Neutron Source Rapid Cycling Synchrotron (CSNS/RCS). The longitudinal and transverse impedance of a fast kicker has been measured for the design and development of the accelerator. The conventional and improved wire methods are employed separately for the benchmark on measurement results. The experimental results compared with impedance simulation by CST PARTICLE STUDIO. Furthermore, it is found in the simulation that the window ferrite and busbar gap are the serious structure of impedance. It is clear by the measurement that the mismatching between the cable and power can produce a serious oscillation which affects longitudinal and vertical impedances. Finally the total impedance of eight kicker systems is obtained by scaling law from the measurements and summarized.

INTRODUCTION

The impedance of vacuum component in accelerator is one reason to cause beam instability even serious beam loss. Therefore, theoretical analyses, simulation and experimental measurement on the benchmark of coupling impedance of accelerator components are crucial tasks in accelerator design, development, and research. The analytical formulas of some vacuum accelerator components are given in references [1-3], and some developed code can be used to simulate coupling impedance, such as ABCI, HFSS and CST. But the coupling impedance with complicate structure is difficult to study through the analytical formula and simulation code. It is necessary to carry out impedance measurement for some accelerator components with bigger and complicated structure.

In case of CSNS/RCS, the extraction kicker represents the most critical impedance [4]. The conventional coaxial-wire and twin-wire method are used to measure longitudinal coupling impedance for benchmark measurements. During the experiments, transverse coupling impedance is first measured by twin-wire and wire loop methods in different frequency range. Because of the connection between kicker and Pulse Form Network (PFN) with cable about 130m long, the mismatch of cable and PFN also contribute to the longitudinal and transverse impedance which is confirmed in the measurements. In order to confirm the validity of impedance measurements, CST PARTICLE STUDIO is used to simulate impedance for kicker.

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THE EXTRACTION KICKER SYSTEM OF CSNS/RCS

There are eight kickers with total kick angle of 20 mrad installed in CSNS/RCS which can create about 130mm central orbit displacement at the entrance of the Lambertson magnet for separation on extracted beam and circulating beam. The parameters of kickers are shown in Table 1. The schematic view of the kicker system is shown in Figure 1.The side strap at the side of the magnet connects the upper and lower busbar plates, and the busbar and window ferrite are located in a vacuum vessel, with 0.58m length. Therefore, the kicker is limped impedance below 100MHz. The busbar is fully isolated from the vessel by ceramic block. The eddy current strip is located in vertical center of ferrite block to reduce longitudinal impedance. The total inductance of the kicker is about 0.9μH, and the capacitance about 30pF mainly comes from end plate in Figure 1. The magnet is powered by PFN via the feedthru and 130 m length cable. The characteristic impedance of the cable is 12.5 Ω, and the impedance of PFN is 6.25 Ω. PFN matches the cable parallel connection with the 12.5 Ω termination when kicker is powered. The saturated reactor is designed to cut PFN when the beam is accelerated, at that time, the cable connects with termination, and it matches. Based on experience from Spallation Neuttron Source (SNS) [5] and Japan Proton Accelerator Research Complex (J-PARC) [6], due to the error of cable and distribution effect of the termination, the cable, termination and PFN mismatch actually, which affect the longitudinal and vertical impedance. Therefore, the impedance is measured for kicker with and without cable, PFN, termination and the power.

Table 1: The Parameters of Eight Kickers

No	K 1	K2	K3-4	K5-6	K7-8
Strength (T)	0.0558	0.0559	0.0526	0.0571	0.0609
Angle(mrad)	2.6	2.2	2.99	2.9	2.76
Length(m)	0.4	0.32	0.45	0.41	0.36
Top time(ns)	>550	>550	>550	>550	>550
width(mm)	155	212	155	157	168
Gap(mm)	136	144	153	141	132
Rise time(ns)	≤250	≤250	≤250	≤250	≤250

Because the No. 2 kicker (K2) is firstly manufactured and tested with PFN and power, we developed the impedance platform and carry out the experiments on it and scaling the total impedance to kicker system.

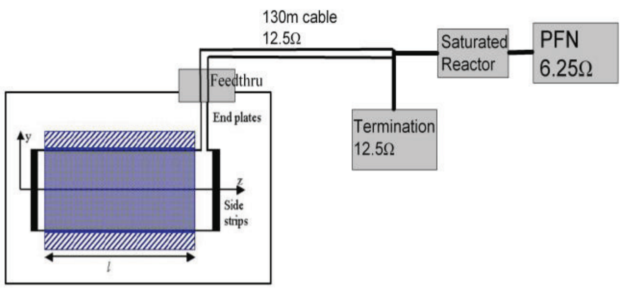

Figure 1: The schematic view of kicker system.

LONGITUDINAL IMPEDANCE

Longitudinal Impedance Measurements by Coaxial-Method

The conventional coaxial method is use in longitudinal impedance measurements. In the platform, an accelerator component with a thin copper wire on its beam axis can be regarded as a two-port microwave circuit, whose forward scatter coefficient can be measured with the Vector Network Analyzer (VNA). Two independent, consecutive measurements of the forward scatter coefficient S21 of the DUT and a smooth reference pipe (REF) with equal length. The longitudinal coupling impedance can be found from the measured transmission coefficients S21 as [7]

$$Z = -2R_c \ln\left(\frac{S_{21,DUT}}{S_{21,REF}}\right), \tag{1}$$

here $S_{21,DUT}$ and $S_{21,REF}$ are the forward scatter coefficient of the DUT and the REF, respectively. R_c is characteristic impedance formed by the reference pipe with the axial copper wire as coaxial transmission line structure which is expressed as

$$R_c = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\left(\frac{b}{a}\right), \tag{2}$$

here μ_0 and ε_0 are the permeability and permittivity of free space, respectively, b is the radius of beam pipe, 125 mm, a is the radius of the wire, 0.25mm, so the characteristic impedance is about 372 Ω. Matching 50Ω of the VNA to R_c of the reference line is achieved by adding a series resistor R_s at the each end of the line, which provides backward matching. The value of R_s is found as

$$R_s = R_c - Z_0. \tag{3}$$

The value of R_s in the measurement is about 320 Ω. Metal resistor is used for matching. The input matching resistor is installed into the DUT, and the output resistor is shielded by the 35mm SUCOBOX [8] on the right. The type of the network analyser - Agilent E5071C is used in the measurements. The longitudinal impedance measurements results are shown in Figure 2.

Two peaks with frequency about 18MHz and 30MHz come from the busbar gap and window ferrite, respectively. The contribution of busbar gap is extracted by the 130 meters length cable, so the peak on 18 MHz disappears for the kicker, cable, PFN and termination connected, but it is clear to see that an oscillation appears when the kicker connected with cable and PFN. The span of oscillation frequency is 0.72MHz. The mismatching between cable and PFN produces oscillation and the oscillation frequency span can be expressed as

$$\Delta f = \frac{c}{2\alpha L}, \tag{4}$$

here, L is the length of the cable, 130 m The factor of the cable medium- the polythene, α=1.6. The spacing in Eq. (4) is 0.72 MHz, which is consistent with the result of the measurement. So, it is confirmed that the oscillation comes from the mismatch between the cable and PFN. The oscillation is invisible on low frequency, and it is increase as the frequency increase, which is the character of distribution effect of the termination.

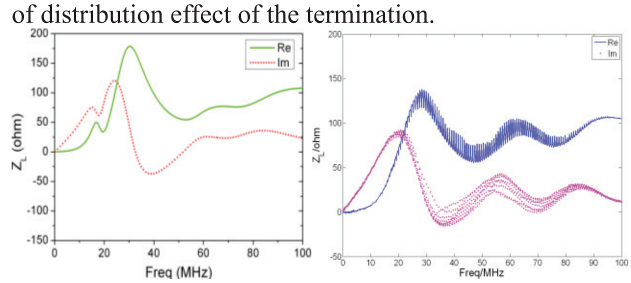

Figure 2: Longitudinal impedance by coaxial-method (left: without connection with cable and PFN; right: connection with the cable and PFN).

Longitudinal Impedance Measurements by Twin-Wire Method

The longitudinal coupling impedance can be measured by twin-wire method with in-phase signal (common-mode) [9]. The network analyzer with two ports is used in the experiments. The spacing of two wires is considered as $2d$, so the characteristic impedance can be calculated as

$$R_c = \frac{1}{4\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\frac{b^2-d^2}{a\cdot(2d-a)}. \tag{5}$$

During the measurements, R_c =440 Ω, 390 Ω metal resistor is used to matching according to Eq (3). The common-mode signal is produced by MINI splitter [10]. Two input signals with the same amplitude and phase separated by splitter are offered. With the transmission coefficient, impedances for kicker without and with the cable, PFN and termination are shown in Figure 3. By comparing the results with Figure 2, it is clear that longitudinal impedance measured by coaxial-method and twin-wire methods is also the same, which benchmarked the measurement methods and its results.

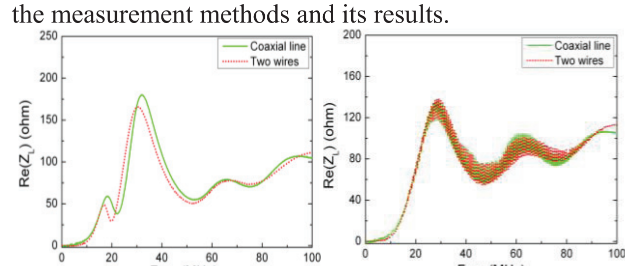

Figure 3: Longitudinal impedance by twin-wire method (left: without connection with cable and PFN; right: connection with the cable and PFN).

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TRANSVERSE IMPEDANCE

Transverse Measurement by Twin-wire

For transverse coupling impedance measurement with wire method, one standard way insert two parallel wires with out of phase signal (differential-mode) into the DUT in order to produce a diploe current moment, which is called twin-wire method and regarded as similar two parallel transmission lines. The forward scatter coefficient S_{21} of twin-wire can be measured by the network analyzer. Metal resistors obtained by Eq. (3) are also used to match characteristic impedance of twin-wire differential-mode signal system which is expressed as [11],

$$R_c = 120[\ln(\frac{d+\sqrt{d^2-a^2}}{a} \times \frac{b^2-d\sqrt{d^2-a^2}}{b^2+d\sqrt{d^2-a^2}})]. \quad (6)$$

For the measurement of CSNS/RCS extraction kicker system, R_c=603 Ω, so resistor is about 250 Ω.

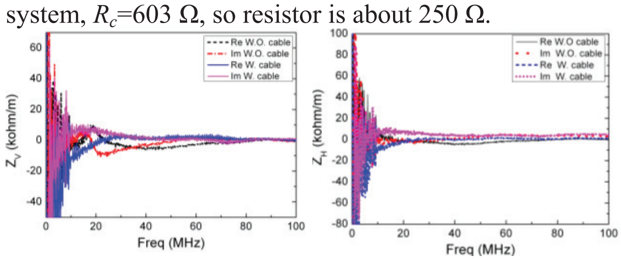

Figure 4: Transverse impedance by twin-wire method.

According to Figure 4, it is clear that there is an impedance peak with frequency 18 MHz without cable PFN and termination, which comes from the contribution of window ferrite and the busbar gap. It disappears with connection of cable, PFN and termination. The frequency span of the oscillation is similar to that of longitudinal impedance. Anyway, the amplitude of vertical coupling impedance is small.

Transverse Measurement by Wire-loop

The transverse impedance below 10 MHz by twin-wire is not good since the error is serious. To extend the measured frequency, one turn loop is used to measure transverse impedance on low frequency. The two wires are shorted at one port, and the hybrid is also used to produce differential-mode signal. The input impedances of the DUT and REF are measured at the other port, so the transverse impedance can be expressed as [12]

$$Z_T = \frac{c}{\omega}\frac{Z^{DUT}-Z^{REF}}{(2d)^2}, \quad (7)$$

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

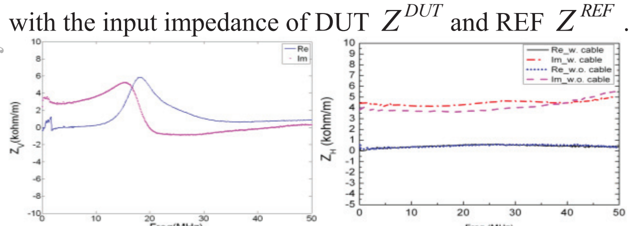

Figure 5: Transverse impedance by wire-loop method.

Shown in Figure 5, the peak with frequency about 18 MHz also appears, which agrees well with the result by twin-wire in Figure 3, and it also disappears for the kicker when the cable, PFN and the termination are connected.

IMPEDANCE SIMULATION

In order to prove the validity of measured impedance, the CST PARTICLE STUDIO [13] is used to simulate the kicker impedance.

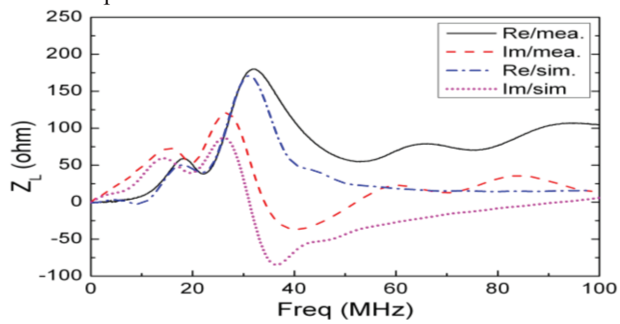

Figure 6: Simulation on longitudinal impedance.

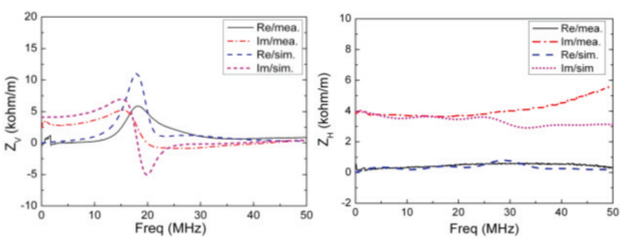

Figure 7: Simulation on transverse impedance.

The simulated results on longitudinal and transverse impedance have been shown in Figure 6 and Figure 7, respectively. It is clear that measured longitudinal impedance agrees well with simulation results below 35 MHz and the difference above 40 MHz is slightly biger. The difference between measured transverse impedance and simulation is also small.

CONCLUSION

Longitudinal and transverse impedances of the fast extraction kicker for CSNS/RCS are measured with coaxial-wire, twin-wire and loop method. Longitudinal impedance by twin-wire agrees well with the impedance by coaxial-wire, so the twin-wire method provides the possibility of simultaneous measurement of longitudinal and transverse impedance. Measured impedances are similar to the simulation results by CST PARTICLE STUDIO. The mismatching from the long cable to PFN affects longitudinal and vertical coupling impedance.

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