COUPLING IMPEDANCE OF THE J-PARC KICKER MAGNETS

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Abstract

Present status of coupling impedance measurements with single- and twin-wire method is described. Devices under test are the extraction kicker magnets of the J-PARC RCS and MR. For transverse coupling impedance measurement a twin-wire and a shifted single-wire were used. In the twin-wire method multi-port network analyzer was successfully utilized. In the way of comparison with the theory of travelling wave kicker, the problem was encountered that the formula does not satisfy causality. The versatile is proposed here, which is to be confirmed in further study.

INTRODUCTION

J-PARC (Japan Proton Accelerator Research Complex) project comprises a 181/400 MeV linac, a 3 GeV rapid-cycling synchrotron (RCS), and a 50 GeV synchrotron (MR) [1]. Five families of kicker magnets are installed at the fast extraction (FX) of the RCS, the injection, injection-abort and fast extraction sections in the MR. This paper covers longitudinal and transverse impedance measurements of the RCS and MR FX kickers. Longitudinal impedance, Z_L, was measured with the coaxial wire method [2]. Transverse impedance, Z_T, has been measured with the twin wire method [2] and shifted single-wire method. For the twin wire method, a multi-port network analyzer was utilized, which may realize simultaneous measurement of Z_L and Z_T with a simple procedure.

FX KICKER MAGNETS IN THE RCS AND MR

Eight traveling-wave kickers will be installed for the RCS FX[3]. The acceptance is width = 280 mm, height = 170 mm, length = 638 mm, L = 1.459 $\mu H/m$, C = 15.04 nF/m, Z = 9.85 Ω and v = 0.0225 c (Fig. 1).

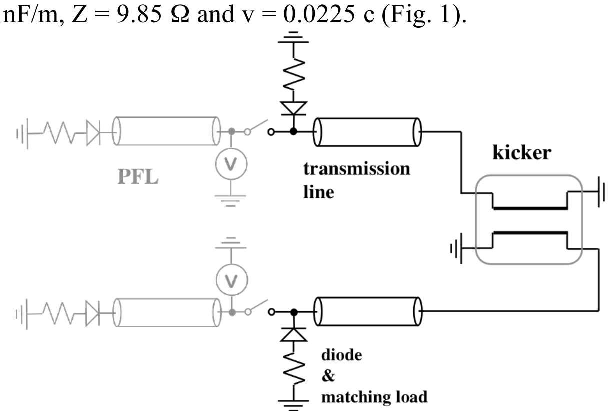

Figure 1 : Schematic of the RCS extraction kicker. Separate power feeder is connected with each kicker coil. Gray colored part was not prepared in this measurement.

Five traveling-wave kickers will be installed for the MR FX[4]. The acceptance is width = 100 mm, height = 110 mm, length = 2424 mm, L = 520 nH/m, C = 21 nF/m, Z = 5 Ω and v = 0.032c (Fig. 2).

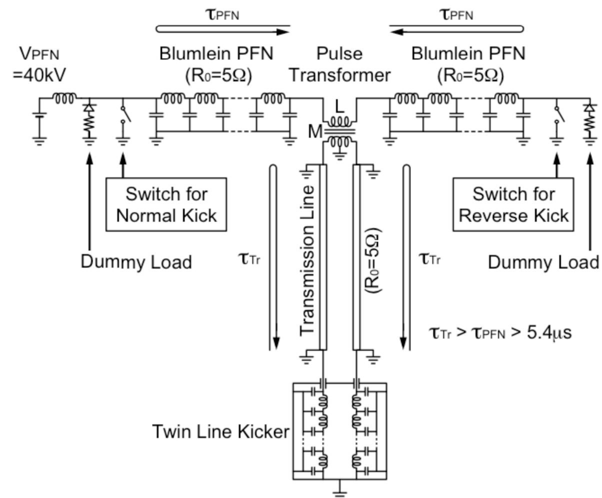

Figure 2: Schematic of the MR extraction kicker.

WIRE MEASUREMENTS

A copper coated piano wire of 0.16 mm diameter or a copper wire of 0.2 mm diameter were stretched in the device under test with appropriate resisters for matching to 50 Ω cables at both ends. Network analyzer (hp 8753E or Rohde and Schwarz ZVT-8) was connected to measure the S21, transmission coefficient.

The measurement of Z_T with twin-wire using multi-port network analyzer was arranged as shown in Fig. 3. In the present measurement, the matching resisters was fit to the difference mode, which will be improved with better configuration matching to both common and difference modes. The Z_T measurement with a single-wire shifting transverse direction, was also examined.

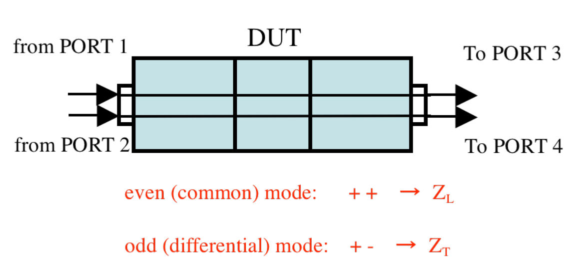

Figure 3: Schematic of twin-wire measurement with a multi-port network analyzer. Cable impedances are 50 Ω. Matching resisters between cables and wires are fit to the differential mode in this case.

The transmission coefficient was converted to the coupling impedance with the standard formulae [2]

$$Z_L = -2Z_c \ln\left[\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right],$$

$$Z_T = \left(\frac{c}{\omega}\right)\frac{Z_{DUT}}{\Delta^2},$$

where Zc is the characteristic impedance of the transmission line consisting of the beam pipe and the wire, S_{21}^{DUT} and S_{21}^{REF} is the transmission coefficient of the DUT and reference pipe, respectively.

RCS FX kicker

The wire measurement was performed for a prototype of "twin" kicker magnets connected with transmission lines and PFL's (Fig. 1). Figure 4 shows the result of Z_L measurement. The spikes are situated at every ~0.55 MHz, which corresponds to twice of the cable and kicker transit time.

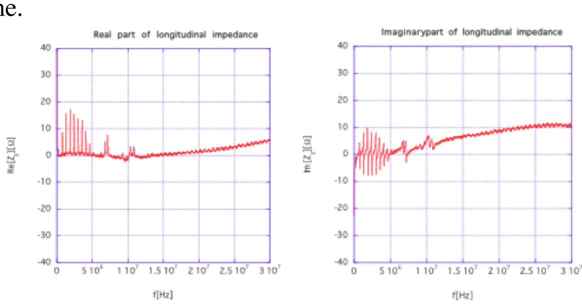

Figure 4 : Z_L of the RCS FX kicker.

For the Z_T measurement, the kicker magnet matched with the kicker characteristic impedance at both ends was examined with the single-wire shifting in the horizontal plane. The coefficient of quadratic position dependence was extracted from the Z_{DUT} data and multiplied by c/ω (Fig. 5). A broad peak situated below ~10 MHz. The validity of this result will be checked to the data with the twin-wire method. There is discrepancy between the data and the formula [5] in the imaginary part, which will be discussed in the next section.

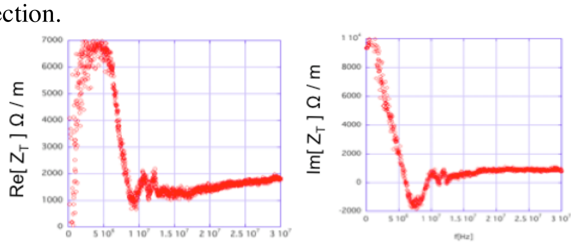

Figure 5 : Z_T of the RCS FX kicker. Horizontal plane. Positive sign corresponds to inductive impedance here.

MR FX kicker

For the Z_L measurement the transmission cables and PFL's were connected to the kicker magnet (Fig. 2). The result is shown in Fig. 6.

For the Z_T measurement, the kicker magnet with an open end and a short-circuited end was examined with the twin-wire and the multi-port network analyzer (using "balance-unbalance conversion" function). Longitudinal impedance Z_L may be evaluated using the common-mode transmission coefficient with twin-wire method. The results (Fig. 7) shows similar global frequency response except a little variation of the absolute value. The difference may come from different kicker termination and wire impedance mismatching of the twin-wire. This may be improved by employing proper matching configuration which matches both differential and common modes. Figure 8 shows measured Z_T. Detailed explanation of resonances is under consideration.

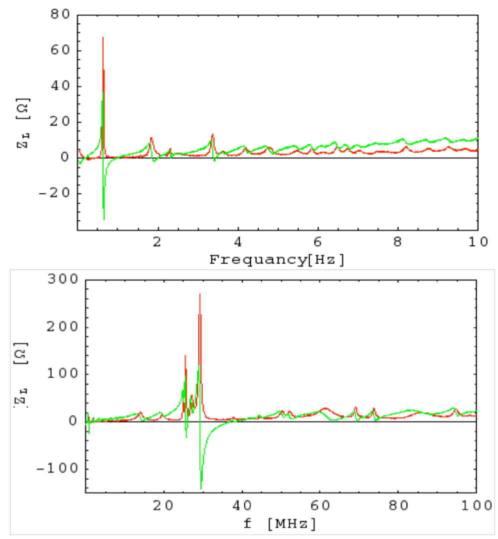

Figure 6 : Z_L of the MR FX kicker measured with coaxial wire method. Red curve: real part, green curve: imaginary part.

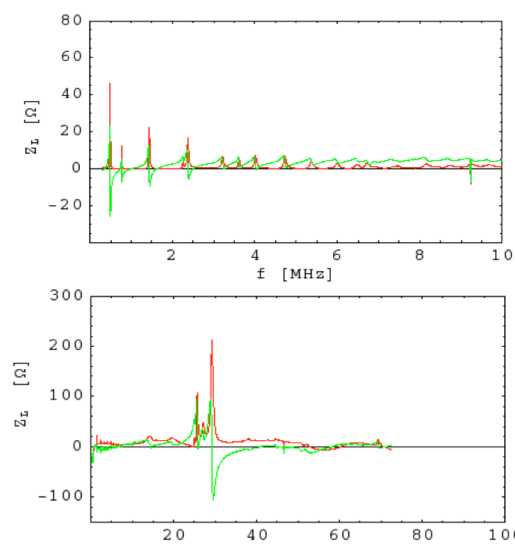

Figure 7 : Z_L of the MR FX kicker measured using common-mode transmission coefficient with the twin-wire method. Red curve: real part, green curve: imaginary part.

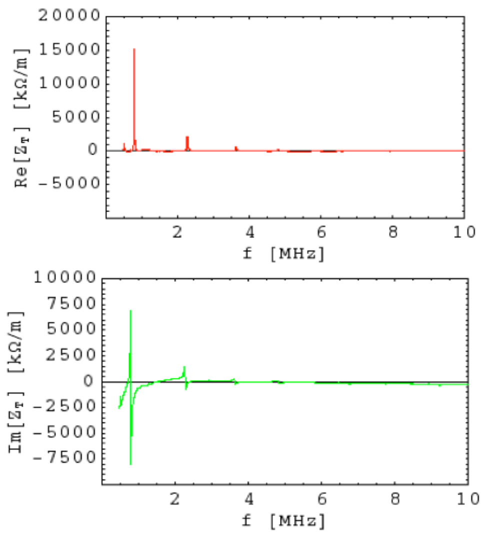

Figure 8 : Z_T of the MR FX kicker. Horizontal plane. Red curve: real part, green curve: imaginary part.

COMPARISON WITH THE THEORY

It is straight forward to apply the impedance formula[5] to the matched-traveling wave kicker (Z_T of the RCS case). However difficulty appears in satisfying causality and imaginary parts of the measured and calculated impedances do not agree with each other as follows.

We define transverse wake function $W_T(z)$ as a function of distance z for $z > 0$, and $W_T(z) = 0$ if $z < 0$. The relation between $W_T(z)$ and the impedance is written as

$$Z_T = j\int_{-\infty}^{\infty} \frac{dz}{c} W_T(z) e^{-j\frac{\omega}{c}z}.$$

The wake of the traveling-wave kicker may be naively expressed as

$$W_T = W_0\left(\Theta(z) - \Theta(z - \frac{Lc}{v}) - \frac{Lc}{v}\delta(z)\right),$$

where W_0 should be a positive constant in order that $W_T'(z)$ becomes positive for z → 0, L/v should be positive due to causality. Therefore the impedance is expressed as

$$Z_T = \frac{W_0}{2\pi c}\int_{-\infty}^{\infty} dz \left(\int_{-\infty}^{\infty} dx \frac{e^{jz\left(x - \frac{\omega}{c}\right)}}{x - j\varepsilon} - \frac{e^{-j\frac{Lc}{v}x} e^{jz\left(x - \frac{\omega}{c}\right)}}{x - j\varepsilon} \right) - j\frac{W_0}{v}L$$

$$= \frac{W_0 L}{v}\left\{ \frac{1 - \cos\left[\omega\frac{L}{v}\right]}{\omega\frac{L}{v}} - j\left(1 - \frac{\sin\left[\omega\frac{L}{v}\right]}{\omega\frac{L}{v}}\right)\right\}.$$

It looks like same as the well-known formula. However, the sign of the imaginary part is negative, which means the impedance is capacitive. This point contradicts both the measured result and the intuition that $\mathrm{Im}[Z_T] > 0$ when $\omega \to 0$. On the other hand the well-known formula is

$$W_T = W_0\left(\Theta(-z) - \Theta(-z - \frac{Lc}{v}) - \frac{Lc}{v}\delta(z)\right),$$

which vanishes in our definition of the wake.

In our measurements, we could find no constant term in the imaginary part of the impedance, which means there is no δ term in the wake function:

$$W_T = W_0\left[\Theta(z) - \Theta\left(z - \frac{Lc}{v}\right)\right].$$

Experiments shows that the imaginary part of the impedance is inductive for $\omega \to 0$, because there is no constant term. This also means there is no instantaneous force in the wake function. The impedance is inductive when $\omega \to 0$. The impedance is in this case

$$Z_T = \frac{W_0 L}{v}\left\{ \frac{1 - \cos\left[\omega\frac{L}{v}\right]}{\omega\frac{L}{v}} + j\frac{\sin\left[\omega\frac{L}{v}\right]}{\omega\frac{L}{v}}\right\}.$$

Oscillatory behavior of the formula may be damped by ferrite core loss in the real kicker.

Similar discussion applies to the longitudinal impedance.

SUMMARY

Longitudinal and transverse impedances of the FX kickers for RCS and MR are measured with coaxial-wire, shifted single-wire and twin-wire. The twin-wire method with multi-port network analyzer seems to provide the possibility of simultaneous measurement of Z_L and Z_T. Further confirmation of the twin-wire method with multi-port network analyzer and the shifted single-wire measurement needs to be performed.

The consistency between the measurement and formula will be also pursued with a reasonable physical explanation.

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