MEASUREMENT OF LONGITUDINAL AND TRANSVERSE IMPEDANCE OF KICKER MAGNETS USING THE COAXIAL WIRE METHOD

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Abstract

Fast kicker magnets are used to inject beam into and eject beam out of the CERN SPS accelerator ring. These kickers are generally ferrite loaded transmission line type magnets with a rectangular shaped aperture through which the beam passes. Unless special precautions are taken the impedance of the ferrite yoke can provoke significant beam induced heating, especially for high intensities. In addition the impedance can contribute to beam instabilities. In this paper different variants of the coaxial wire method, both for measuring longitudinal and transverse impedance, are briefly discussed in a tutorial manner and do's and don'ts are shown on practical examples. In addition the results of several impedance measurements for SPS kickers are presented and compared with analytical calculations.

INTRODUCTION

The fast kicker magnets used in the CERN SPS ring are generally ferrite loaded transmission line type magnets with a rectangular shaped aperture of dimensions H_{ap} by V_{ap} (Fig. 1). These magnets consist of “cells” to approximate a coaxial cable: C-cores of magnetic material are sandwiched between High Voltage (HV) capacitance plates.

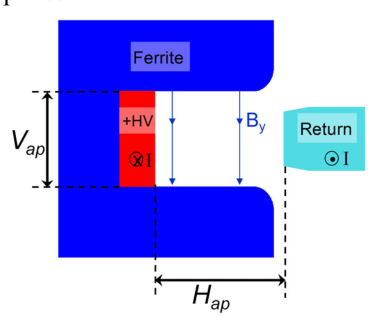

Figure 1: Simplified cross-section of a kicker magnet.

Beam coupling impedance is a critical issue in many accelerators: longitudinal and transverse impedance may drive instabilities and cause undesired tune shifts. In many cases the beam coupling impedance of a kicker magnet can be determined analytically or by simulations. In some situations, however, due to complex geometries or not very well known electromagnetic material parameters, measurements are required.

Wire measurements rely on the fact that an ultra relativistic beam has a very similar electromagnetic field distribution to that of a TEM line [1]. Standard wire measurement techniques are described in [2]. Generally speaking, the wire diameter (d) should be as small as possible to get an high line impedance [1]. A wire diameter of 0.5 mm was used for all measurements reported in this paper. Practical issues related to wire measurements, such as sag, are discussed in [1]. An Agilent E5071C two-port Vector Network Analyser (VNA) was used for the measurements reported in this paper: an IF bandwidth of 1 kHz was used.

WIRE MEASUREMENT TECHNIQUES

Longitudinal Impedance Measurement

a) Single Wire Transmission

For a longitudinal measurement (Fig. 2) a single wire is inserted into the Device Under Test (DUT) and S_{21}, the signal transmission, is measured. The VNA and connecting cables have a characteristic impedance (Z_0) of 50 Ω. The TEM line consists of the kicker magnet (DUT) and the wire.

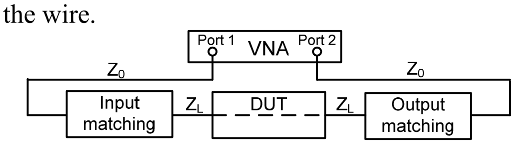

Figure 2: Schematic of single wire measurement setup.

The SPS dump system consists of 2 vertical kickers (MKDV1 and MKDV2), and 3 horizontal kickers (MKDH1, MKDH2 and MKDH3) [3]: measurements have been carried out on several of these kickers. These dump kickers are ~30 years old: at the time of fabrication beam impedance was less of an issue. Hence no “transition pieces” were installed between the ends of a magnet and the vacuum tank. Thus, during the measurements, some energy can bypass the kicker magnet giving artificially low beam coupling impedance at frequencies above a few hundred MHz: in addition, at certain frequencies, resonances can be excited in the vacuum tank.

Measurements are typically made over a frequency range of 100 kHz to 2 GHz. To minimize reflections, the impedance seen by the DUT can be matched over this range [1]. One-way matching, from the DUT to Z_0, was achieved with a series high quality carbon resistor at each side of the DUT. Reflections back to the VNA were reduced using an attenuator on the remote end of each measurement cable (Fig. 3). To ensure reliable and repeatable measurements only N-Type connectors were used.

Each matching resistor was initially mounted in a 35 mm long SucoBox #2 (Fig. 3). A through calibration was performed to account for the frequency dependence of the resistance in the calibration. A less convenient, but a better approach, is to solder the matching resistor directly to the measurement wire, inside each

SucoBox #1, and dispense with SucoBoxes #2. Whichever method is used, the calibration of the VNA must always be performed at a single reference plane.

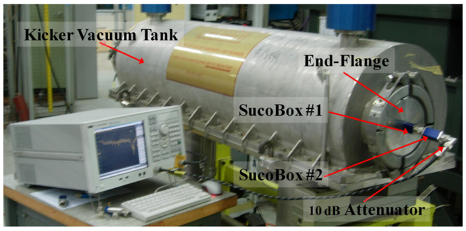

Figure 3: Longitudinal impedance measurement setup.

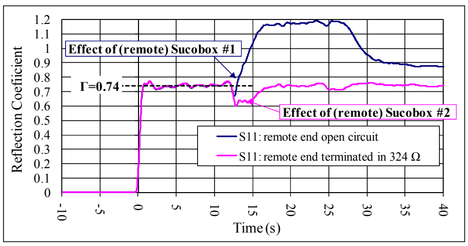

Figure 4: S_{11} measurement for the MKDH3 kicker.

Figure 4 shows the S_{11} impulse response for the MKDH3 kicker with the remote end (a) open-circuit and (b) terminated in 324 Ω: the notch between 12.5 ns and 15 ns is attributable to the combined effect of SucoBoxes #1 and #2 at the remote end of the magnet. The characteristic impedance of the DUT can be determined from the reflection coefficient (Γ) using Eq. 1:

$$Z_L = Z_0\left(\frac{1+\Gamma}{1-\Gamma}\right) = 50\left(\frac{1+0.74}{1-0.74}\right) = 335\,\Omega \qquad (1)$$

The characteristic impedance, Z_L, of the kicker shown in Fig. 1 is given by Eq. 11.4 in [4]: for MKDH3, H_{ap}=105 mm [3], hence Z_L=335 Ω, i.e. the same value as given by Eq. 1.

To determine the longitudinal impedance, S_{21} for MKDH3 was measured: 285 Ω matching resistors were used in SucoBoxes #2. The complex but linear $S_{21,DUT}$ must be compared to an ideal reference line $S_{21,ref}$ [5]. $S_{21,ref}$, for a homogeneous matched line, corresponds to the electrical length ($\theta = 2\pi Lf/c$) of the DUT [1], where: L is the structures length, f is frequency and c is the velocity of light in free space. For a kicker magnet an improved log formula is normally the best approximation for the longitudinal impedance (for $\theta \geq 1$) [1].

The Real Longitudinal Coupling Impedance (RLCI), calculated from measurements, shows unrealistic resonances (Fig. 5). Hence the measurement was repeated with the VNA function “Time Domain Gating On” to eliminate ringing after the first zero crossing of the (real) low pass impulse response. The resultant RLIC is also shown in Fig. 5; analytically calculated longitudinal impedance, from Eq. (27) in [5], which assumes an infinitely long (2D) homogeneous kicker magnet, is also shown. The permeability and permittivity of ferrite were utilized in evaluating Eq. (27) in [5], whereas the magnetic material used in the MKDH kickers is 0.35 mm thick laminated steel: the laminations probably have a significant effect upon the impedance. The MKDH3 measurement should be repeated, with the matching resistors inside SucoBoxes #1, and a full 2-port calibration made at 50 Ω (see below).

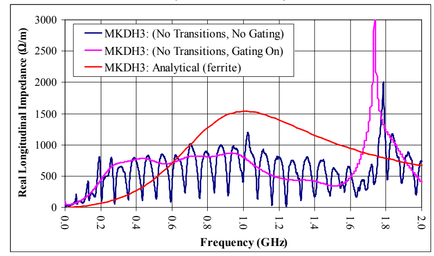

Figure 5: Measured and theoretical RLCI for MKDH3.

Figure 6 shows RLCI measurements carried out on MKE (extraction) magnets, with and without serigraphy of the ferrite [3], together with analytical calculations for a kicker magnet without serigraphy. The MKEs are 7-cell kickers; each cell is ~0.24 m long. The analytical and measured RLCI are in reasonable agreement to 1 GHz. The measurement data shows high frequency oscillations from ~0.45 GHz; a λ/2 resonance, based on the length of the serigraphy fingers of 2 adjacent cells (0.42 m) in free space is 0.38 GHz. It may be possible to smear these resonances by choosing appropriate lengths of serigraphic fingers: simulations are planned to study this.

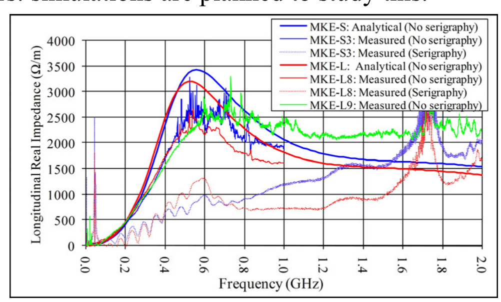

Figure 6: Measured and theoretical RLCI for MKEs.

Resonances below 100 MHz are only present with serigraphy (Fig. 6). With serigraphy there is a strong resonance in the frequency range of 47 MHz to 49 MHz: this is close to a λ/4 resonance, based on the magnet length (1.7 m→45 MHz). Detailed measurements show that these resonances are affected by the external circuit on the output of the magnet (resistor termination or short-circuit): further measurements are needed to determine whether capacitor boxes, which are external to the MKE magnets, also affect resonances. With the correct output termination and capacitor boxes present, the presence or absence of 200 m of RG220U cable on the input of the magnet has a small, but measurable, effect.

Theoretical and measured RLCI for MKDV1 are shown in Fig. 7: the measurements were carried out with and without transition pieces. Without transition pieces resonances start at ~0.2 GHz, which corresponds to λ/2 based on the magnet length (2.55m): the minima of the resonances are, up to 1.6 GHz, in good agreement with the analytical RLCI.

Measurements were initially performed with a matching resistor inside each SucoBox #2: a through calibration of the VNA included these SucoBoxes. However, since a broadband impedance of ~315 Ω was not available, it was not possible to carry out a full 2-port calibration. As a result the measured S_{21} had oscillations which resulted in an unrealistic RLCI. Thus, instead, the matching resistors were included in the SucoBoxes #1, attached to each end flange (Fig. 3), and SucoBoxes #2 were dispensed with. A full 2-port calibration was carried out at 50 Ω: the total (DC) resistance of the two matching resistors was subtracted from the measured RLCI. The resulting RLCI, with and without gating applied, is shown in Fig. 7: the effect of gating is to suppress some minor oscillations in the RLCI. Both curves are in good agreement with the analytical calculation up to 1.6 GHz.

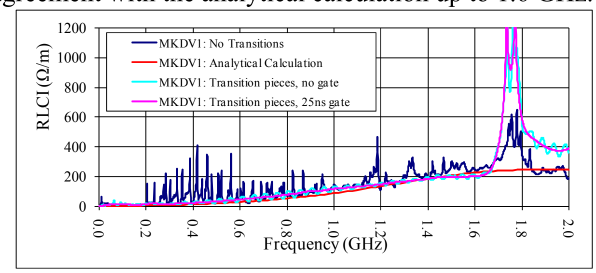

Figure 7: RLCI for MKDV1.

b) Resonant Method

For small losses a resonant measurement is a better approach, since very high sensitivity can be obtained [1]. The resonant method may be required when the magnet aperture has a small ratio for H_{ap} to V_{ap} or when effective impedance reduction techniques have been applied.

Transverse Impedance Measurement

For realistic beam dynamics simulations both dipolar and quadrupolar impedances are needed [6]: hence both 1-wire and 2-wire measurements are required. To obtain transverse dipolar impedance, in both x and y planes, a two-wire measurement is made in each plane [6]. One-wire measurements, at two transverse offsets, are needed to obtain the difference and sum of the dipolar and quadrupolar horizontal and vertical transverse impedance.

a) Two-Wire Transmission

Initially a two-wire transmission method was used to determine the Transverse Dipolar Horizontal Impedance (TDHI) of MKDH3: the two-wires were separated by 28 mm in H_{ap}. From Eq. (2.17) in [1], the difference-mode impedance of this two-wire line in free space is 566 Ω (an S_{11} measurement gave $\Gamma = 0.69$, which corresponds to 283 Ω to a virtual ground mid-way between the two wires i.e. 546 Ω between wires). The phase opposition between the two wires was obtained by splitting the input signal in a 180° hybrid and recombining it at the output in the same way. For one-way matching, a 223 Ω resistor was connected in each of the 4 SucoBoxes #2 (this measurement was made before it was shown that the 2nd SucoBoxes are undesirable) and a through calibration performed. The measured S_{21} for MKDH3 showed oscillations which could exceed a value of 1: this is non-physical and is thought to be due to not having a broadband load of 273 Ω to carry out a full 2-port calibration of the VNA. The measurement was repeated using the two wire resonant method.

b) Two-Wire Resonant Method

The two wires placed in the magnet (see above) were used for the resonant measurement: 4 SucoBoxes #2, each with a small "through" capacitive coupling, were connected to each of the 4 SucoBoxes#1. The "through" capacitive coupling was achieved using a stiff wire and adjusting its position, relative to the centre pin of the connector on the DUT side, to be visually the same. An S_{11} measurement was made and the capacitors on the input side were both adjusted (ensuring that they were visually identical) to eliminate notches in S_{11}. The same procedure was repeated for S_{22}. In addition the through capacitance was such that S_{21} never exceeded −30 dB throughout the measurement frequency range. Fig. 8 shows the resulting real TDHI for MKDH3: analytical calculations are not available for a laminated steel core.

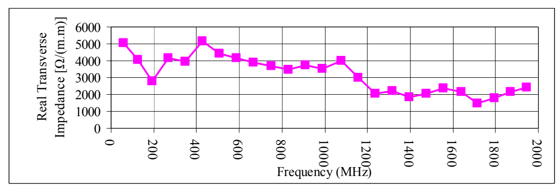

Figure 8: Real TDHI for MKDH3.

CONCLUSIONS

Variants of the coaxial wire method for measuring longitudinal and transverse impedance have been briefly presented. It has been demonstrated that that only a single SucoBox should be used at each end of a wire and a full 2-port calibration of the VNA carried out at 50 Ω. For a ferrite loaded kicker magnet, without any beam coupling impedance reduction techniques, the analytical and measured RLCI are in reasonable agreement up to 1 GHz.

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