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TRANSVERSE IMPEDANCE MEASUREMENTS AND SIMULATIONS OF THE LHC INJECTION KICKER MAGNET*

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Abstract

Kicker magnets contribute significantly to the total impedance budget of many accelerators. Of particular interest, from a beam stability point of view, is the transverse beam coupling impedance (TBCI) that is used to determine intensity limitations of a machine. Until recently, no conclusive TBCI data for the Large Hadron Collider (LHC) injection kicker magnets (MKIs) was available. However, in view of the upgrade of the MKIs for the High-Luminosity LHC (HL-LHC) project, the TBCI of the existing design needed to be estimated to be used as reference for an upgraded version. To that end, electromagnetic simulations were carried out to determine the dipolar and quadrupolar components of the TBCI in the two transverse planes. To validate the simulations, test bench measurements were performed using standard RF measurement techniques. In the present work, the results from TBCI simulations and measurements are reported and compared. Detailed descriptions of the methods and techniques used as well as the realization of the experimental set-up are also given.

INTRODUCTION

The TBCI is a frequency domain quantity defined as the Fourier transform of the transverse wake potential [1,2]. In a general setting the two components of interest can be written as $Z_u(x_s, x_t, y_s, y_t; \omega)$, where u takes the values x, y for each of the two transverse planes under consideration, with $x_{s/t}$ and $y_{s/t}$ denoting the horizontal and vertical displacement of the source/test particle, respectively. Assuming absence of coupling between the two planes and transverse displacements small enough so that second and higher order terms are considered negligible, the two components of the TBCI function can be expanded as [1]

$$Z_u(\omega) \approx Z_u^0(\omega) + u_s\, Z_u^{dip}(\omega) + u_t\, Z_u^{quad}(\omega). \qquad (1)$$

In the above notation, $Z_u^0(\omega)$ is the component of the transverse impedance that is independent of the particles' offsets, while $Z_u^{dip/quad}(\omega)$ is the term linearly proportional to offset of the source/test particle, referred to as dipolar (or driving) and quadrupolar (or detuning) components respectively.

ELECTROMAGNETIC SIMULATIONS

Method

Using CST [3] the zeroth order terms of the impedance can be evaluated by maintaining both source and test beam paths at their nominal positions in the centre of the magnet. To obtain the linear terms, the source/test beam path is shifted by a predefined distance, while the other is kept at its unperturbed position, and the total transverse impedance $Z_u(\omega)$ is estimated. Then, assuming the validity of Eq. 1, the dipolar/quadrupolar components can be computed as $Z_u^{dip/quad} = \frac{1}{u_{s/t}}(Z_u(\omega) - Z_u^0(\omega))$. The perturbed paths must be placed sufficiently close to the nominal one, so that the linear approximation holds and the simulation domain must be properly set so that there is sufficient resolution between the two paths. Due to long simulation times and strict timetables, a parametric analysis for the path displacement was not adopted. Instead, a value of 1 mm was chosen, ~4.6% of the pipe radius, nevertheless, the results will be validated with measurements.

Results

The dipolar and quadrupolar components of the MKI transverse impedance as estimated from CST simulations are shown in Figs. 1 and 2, respectively. As discussed in [4] modes at frequencies above 50 MHz were also observed but with significantly lower shunt impedance values. Therefore, the present work focuses on the frequency range 5-50 MHz.

For the dipolar component in the horizontal plane 4 modes were observed two of which have shunt impedance values of a few MΩ/m. Moreover, in the vertical plane, two low frequency modes can be identified, of the same order of magnitude as the horizontal ones. Wakelengths of 750 m were used in the simulations which led to a frequency resolution of 400 kHz for the corresponding frequency domain signals. Due to time restrictions, simulations of longer wakelengths were not performed and the accuracy of the sampling rate will be validated with measurements.

As seen in Fig. 2 the real parts of the horizontal and vertical quadrupolar components of the MKI are equal in magnitude but opposite in sign. This can be attributed to the fact that the MKI beam screen is symmetric under 90° rotations along most of its length [5]. Four modes are observed below 50 MHz with the strongest ones found around 7.4 MHz and 11.5 MHz having shunt impedance values of about 2 MΩ/m and 1 MΩ/m, respectively.

TEST BENCH MEASUREMENTS

Method

To measure the dipolar TBCI of the MKI, the 2-wire method was used [6]. The technique requires that two wires displaced at equal distances from the nominal beam path are stretched along the device under test (DUT) and excited

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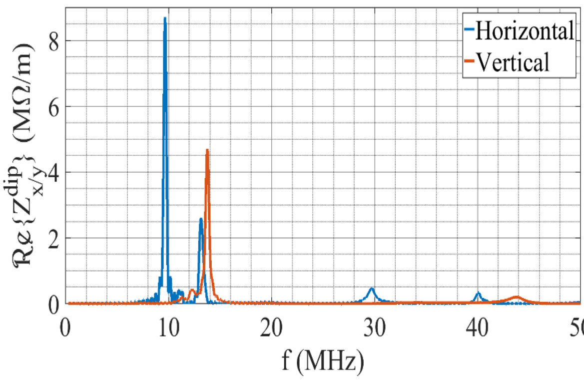

Figure 1: Real part of horizontal and vertical dipolar MKI impedance (CST predictions).

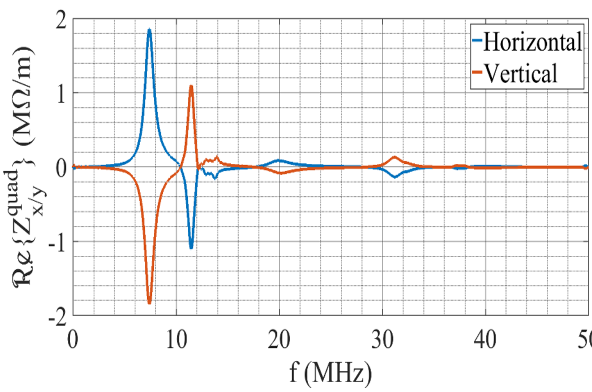

Figure 2: Real part of horizontal and vertical quadrupolar MKI impedance (CST predictions).

with signals of opposite phase. In this way a dipolar electromagnetic field is created and allowed to propagate within the structure. By measuring the losses caused by its passage through the DUT, the resonant modes that this field pattern excites within the DUT can be determined.

Set-up

Since only a 2-port vector network analyser (VNA) was available, the source signal was first sent to a 180°-hybrid, to be extracted with 0° and 180° phase difference at two of its ports, with the fourth port being matched to a 50 Ω resistor. The output signals were then transferred to the stretched wires using 50 Ω cables featuring an N type connector at one end and an SMA at the other. The latter were chosen at the DUT side in order to overcome spatial limitations and to house both wires with their matching resistors in a single SUCOBOX, that was directly attached to the MKI flange, as shown in Fig. 3. An identical configuration was used at the output of the magnet to recombine the signals travelling in the two wires and to feed it back to the VNA. A schematic of the set-up can be seen in Fig. 4.

A parameter of critical importance for the 2-wire measurement is the ratio of the separation between the centres of the two wires (Δ) to the beam pipe aperture (b). In order

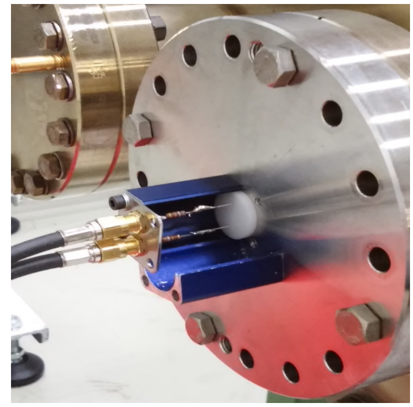

Figure 3: SMA connections to matching resistors in a SUCOBOX attached to the MKI flange.

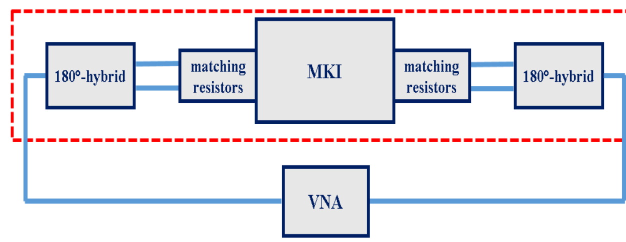

Figure 4: Sketch of the configuration for the 2-wire measurement method.

to achieve a good trade-off between validity of the 2-wire approximation, $\Delta \ll b$, and clarity in the measured signal, a ratio of $\frac{\Delta}{b} \simeq 0.3$ is considered optimal [6,7]. For the present work the beam pipe aperture was defined as the distance, in a transverse cross section, between the inner middle points of two oppositely facing screen conductors, i.e. $b = 43.7$ mm. Then, the wires' separation was chosen to be $\Delta = 10$ mm, leading to a $\frac{\Delta}{b} \approx 0.23$. Silver coated copper wires with diameter of $d = 0.5$ mm were chosen and carbon resistors of 171.5 Ω were used in the matching circuit.

Analysis

The S_{21} parameter of the 2-port network consisting of the two 180°-hybrids, the connecting cables, the four matching resistors and the MKI was measured. As can be seen in Fig. 5 the measured signal is dominated by background "noise" caused by the remnant mismatch in the set-up. However, the dipolar modes of the DUT can still be recognised as sudden drops in the measured signal.

In order to convert the measured signals to TBCI values, the noise had to be removed. As it can be observed in Fig. 5, the background is very similar in the two measurements and this behaviour can be attributed to the geometry of the MKI beam screen. Its symmetry under 90° rotations along most of its length leads to DUTs with very similar characteristic impedances and, in turn, of very similar mismatches for the two set-ups. As a result, a direct subtraction of the two

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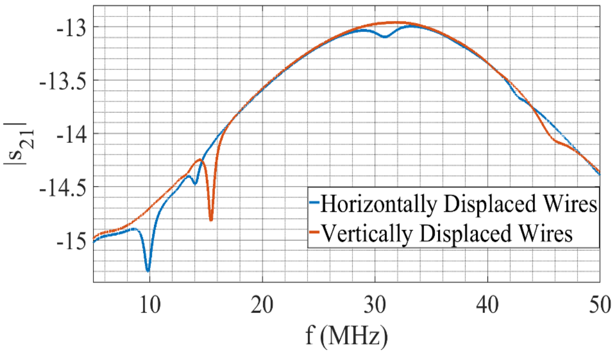

Figure 5: Measured signal in the two configurations.

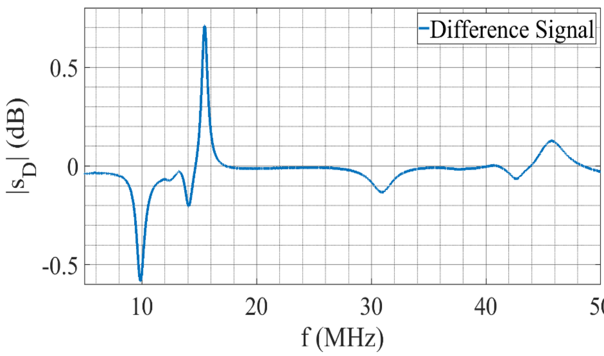

Figure 6: Difference of the two measured signals.

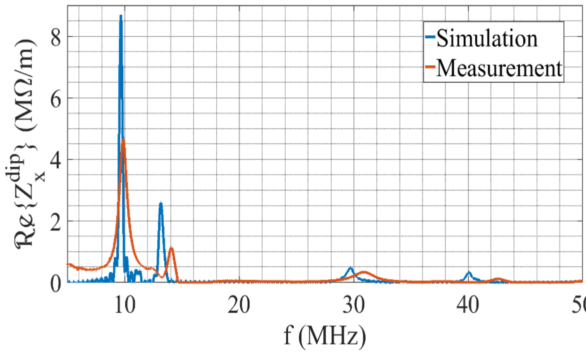

Figure 7: Real part of the MKI horizontal dipolar impedance.

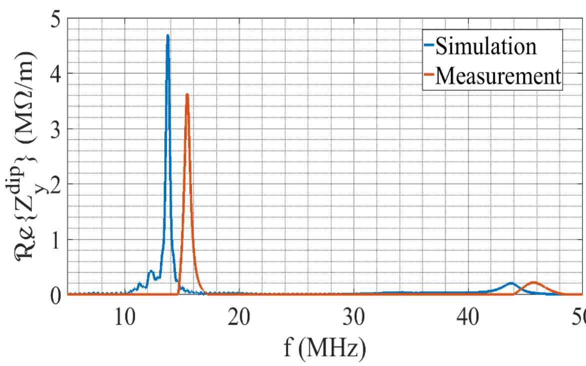

Figure 8: Real part of the MKI vertical dipolar impedance.

signals will remove the background noise and will retain the dipolar TBCI information.

The difference signal, defined as $s_D = s_X - s_Y$, where s_X and s_Y are the measured signals when the wires are displaced horizontally and vertically respectively, is plotted in Fig. 6. It can be easily understood that s_D contains information both for the horizontal, negative peaks, and for the vertical dipolar impedance, positive peaks. To properly convert the signal to horizontal/vertical dipolar TBCI values the positive/negative offsets of the signal were manually set to zero as they do not carry useful information for the respective plane. After removing the irrelevant part of the signal for each impedance component, the signal was converted to longitudinal impedance according to the log-formula, $Z_L = -2\, Z_0 \log(s_D)$, and finally to transverse impedance, using the Panowsky-Wenzel theorem, via $Z_T = \frac{cZ_L}{2\pi f \Delta}$ as described in [6].

Comparison to Measurements

The results obtained with the two approaches are compared in Figs. 7 and 8 for the horizontal and vertical dipolar impedance respectively. It can be seen that a good agreement both in the resonant frequencies and in the order of magnitude of the shunt impedance values in both transverse planes is obtained. Discrepancies of the order of a few MHz can be attributed to the presence of the two wires that modify the resonances of the structure. Moreover, discrepancies in the shunt impedance values and the Q-factors may be caused by inaccuracies in the material models used in simulations. Due to the latter uncertainties, the observed agreement is considered sufficient to establish confidence in the dipolar transverse impedance model of the MKI.

CONCLUSION AND OUTLOOK

TBCI simulations and measurements were carried out for the LHC injection kickers. The results are in good agreement indicating that there are some strong modes below 50 MHz with shunt impedance values in the order of a few MΩ/m. As a result, the inclusion of the MKIs in the LHC transverse impedance database, is expected to improve the accuracy of the LHC transverse impedance model and investigation of its effect on the simulated instability thresholds. Finally, the results and the obtained experience will be used as a reference and guidance for measurement on the upgraded MKI (MKI-Cool [8]) that is scheduled for installation in the LHC tunnel during Long Shutdown 2.

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