EFFECT OF THE TEM MODE ON THE KICKER IMPEDANCE

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Abstract

The kickers are major contributors to the CERN SPS beam coupling impedance. As such, they may represent a limitation to increasing the SPS bunch current in the frame of a luminosity upgrade of the LHC. The C-Magnet supports a transverse electromagnetic (TEM) mode due to the presence of two conductors. Due to the finite length of the structure this TEM mode affects the impedance below a certain frequency (when the penetration depth in the ferrite becomes comparable to the magnetic circuit length). A theoretical model was developed to take into account also the impedance contribution due to the TEM mode. The model is found to be in good agreement with CST 3D electromagnetic (EM) simulations. It allows for generic terminations in the longitudinal direction. An example of kicker is analyzed taking into account also the external cables.

INTRODUCTION

A device of finite length inserted in the vacuum tank and equipped with an inner conductor can support propagation of a Quasi-TEM mode when interacting with the beam. The device behaves as a transmission line formed by the vacuum tank and the inner conductor which are continued on the external cables and closed on the appropriate circuit terminations. The TEM mode affects the impedance below a certain frequency (when the field penetration in the ferrite becomes comparable to the magnetic circuit length). This behaviour disappears as soon as we allow for 2-D geometries (infinite in the longitudinal direction) because the transverse TEM mode arises at the discontinuities which in this case are moved to infinity. For this reason, if we want to take into account the interaction of the beam with the TEM mode, we must resort to a 3D C-Magnet model.

Up to now the theoretical calculation of the impedance contribution of kicker magnet has been based on the so called Tsutsui model [1]. Since this model cannot support TEM mode, it is expected to be valid only above a certain frequency (when the TEM mode has no effect because the penetration depth in the ferrite is small compared to the magnetic circuit length [2]). Contrary to the Tsutsui model the C-Magnet model (CMM) of Fig.1 can support a TEM mode but as described before its effect on the impedance disappears if we do not account for finite length. All the contributions to the impedance (constant, driving, detuning, longitudinal) of a 2-D model of the C-Magnet without inner conductor were calculated in [2]. To take into account the TEM impedance contribution this model should be modified accounting for the inner conductor (which complicates the field matching conditions) and the finite length resorting to a mode matching technique. Since already in [2] the calculation was very complicated and we had to find a trade-off between several numerical issues we decided to resort to a circuit model for the calculation of this TEM impedance contribution. In the 1979 Sacherer and Nassibian [3] calculated the TEM impedance contribution for longitudinal and dipolar horizontal impedances for the CMM. Starting from this study we reviewed this calculation including also the non TEM contribution. We calculated all the impedance terms for the CMM and successfully benchmarked the results with EM simulations.

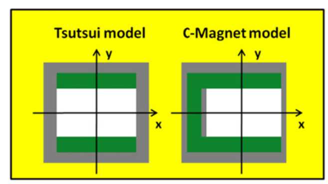

Figure 1: Geometric models for impedance calculation: ferrite in green, PEC in gray and vacuum in white.

Figure 2, shows a simulation of the driving horizontal impedance which reveals the features previously discussed. In this Figure we can clearly see that Tsutsui model and CMM are in perfect agreement above few hundreds of MHz but significantly differ below a certain frequency.

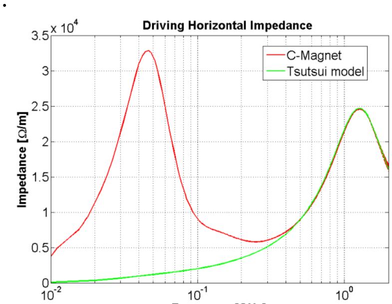

Figure 2: Simulations of the real part of the driving horizontal impedance for an MKP-L (SPS Injection kicker) module using different models.

THEORETICAL MODEL

The broadband beam coupling impedance of the CMM kicker of Fig.1 is calculated using the superposition of the effects. Indeed for these devices the impedance arises from core losses and coupling to the magnet winding.

The first contribution can be easily calculated resorting to the Tsutsui model (see Fig. 1). In this approximation the core losses could be underestimated because we neglect the additional ferrite block of the CMM with respect to the Tsutsui simplified structure. This effect should be negligible because at high frequency the penetration depth in the ferrite become so small that the Tsutsui model approximates perfectly the CMM and at low frequency the core losses become negligible as the ferrite is transparent for the beam.

The second contribution due to the coupling with the magnet winding that we called TEM contribution can be calculated approximating the kicker as an ideal transformer as explained in [4] where this circuit model was applied for the calculation of the transverse beam coupling impedance of a frame-magnet [2] in the kick direction.

The results obtained in [4] differ from the results obtained in [3] for the imaginary part. In this paper the authors agree with the analysis performed in [4] and using the same approach they have calculated the longitudinal and transverse impedances of a C-Magnet kicker. The C-Magnet kicker has also a constant term [5] (the horizontal impedance is different from zero also when the beam is in the geometrical center of the structure) because it has no left/right symmetry.

Total Impedance of the Kicker

Since we separated the core losses contribution from the TEM contribution the total impedances of the kicker (longitudinal, constant, driving and detuning) can be obtained applying the superposition of the effects as

$$Z^{kicker} = Z_{TEM} + Z_M \tag{1}$$

where Z_{TEM} is the impedance contribution due to the TEM propagation and Z_M the impedance contribution due to core losses. Figure 3 shows the equivalent circuit of our model:

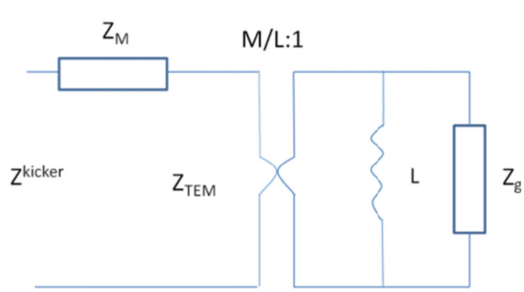

Figure 3: Circuit model of the kicker including cables. L is the inductance of the magnet circuit, Z_g the external impedance including cables, M the mutual inductance of the magnet.

TEM Impedance Contributions

In order to have a full characterization in terms of beam coupling impedance we are interested in knowing the longitudinal and transverse (horizontal and vertical) driving and detuning impedances [5] of the kicker magnet due to the TEM propagation.

As calculated in [3] the mutual inductance M for a C-Magnet of constant gap $2b$ is given by:

$$M = \frac{(x+a)\mu_0 l}{2b} \tag{2}$$

where x is the beam position, a e b are respectively the horizontal and vertical half aperture of the magnet winding, l is the kicker length and μ_0 is the vacuum permeability. The TEM contribution to the longitudinal impedance can be then calculated from the circuit model of Fig.3:

$$Z_L = \frac{1}{4}\frac{j\omega L Z_g}{j\omega L + Z_g} \tag{3}$$

The horizontal driving impedance is calculated from the longitudinal [3] as follows:

$$Z_x = \frac{c}{\omega a^2} Z_L = \frac{c}{4\omega a^2}\frac{j\omega L Z_g}{j\omega L + Z_g} \tag{4}$$

The vertical driving impedance is related only to core losses since is not coupled to the external circuit. For the same reasons also the detuning vertical and horizontal impedances are considered to be zero.

The constant impedance [5] of the CMM can be calculated as the transverse impedance of mode 0 from the longitudinal impedance using the Panofsky-Wenzel theorem [6]:

$$Z_{const} = \frac{c}{4\omega a}\frac{j\omega L Z_g}{j\omega L + Z_g} \tag{5}$$

The model allows for any longitudinal boundary condition, Z_g can be changed in order to implement different boundary conditions and the effect of external cables can be easily included.

Core Losses Contributions

As previously said the core losses contribution Z_M (see Fig. 3) to the coupling impedance is well approximated by the Tsutsui model [1]. Longitudinal, driving and detuning horizontal and vertical impedances are calculated in [1, 7, 8].

COMPARISON WITH 3D SIMULATIONS

The model is benchmarked with the results of the Wakefield solver of CST Microwave Studio. The code was demonstrated to be a reliable instrument for impedance characterization of ferrite loaded kickers [9]. In the simulations to account also for the finite length the simulation box (vacuum tank) is longer than the kicker length and is terminated with a Perfectly Matched Layer (PML) boundary conditions. Then in order to compare with the CST simulations in our model the kicker is

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terminated at both ends with its frequency dependent characteristic impedance

$$Z_g = Z_0 \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}} \qquad (6)$$

where Z_0 is the free space impedance and μ_{eff} and ε_{eff} are calculated as the effective permeability and permittivity of the kicker magnet approximated as an equivalent microstrip [10]. Figure 4 shows the comparison between the CST simulations and our model for an MKP module in the CMM approximation. The simulation and the theoretical model are in very good agreement over the whole explored frequency range. The small difference below 200 MHz could be related to the TEM approximation of the Quasi-TEM mode supported by the kicker module. Figure 5 shows the longitudinal impedance of an MKP module in the CMM approximation. Also in this case our model is in very good agreement with the CST simulations. The good agreement in the low frequency peak (around 55 MHz) is remarkable. This peak is related to the contribution of the TEM mode to the longitudinal impedance (Eq. 3).

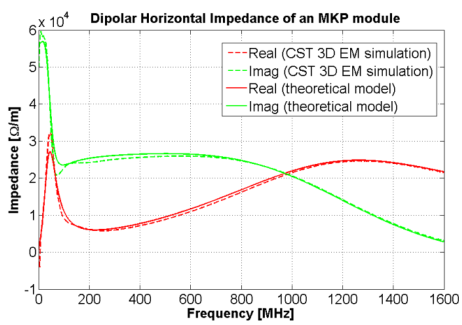

Figure 4: Comparison of the driving horizontal impedance for an MKP-L module of CST 3D TD simulations (dashed lines) with the theoretical model (full lines).

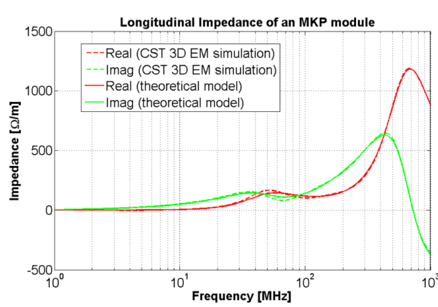

Figure 5: Comparison of the longitudinal impedance for an MKP-L module of CST 3D TD simulations (dashed lines) with the theoretical model (full lines).

EFFECT OF THE EXTERNAL CIRCUITS

The ejection kicker of the PSB is analyzed as example of interest for our model. In the PSB the cables that connect the kicker to the generator are not as long as in the SPS where the cables are roughly 200 meters and can then determine resonances at frequencies relatively high. The external impedance including cables can be calculated resorting to the transmission line theory. Figure 6 shows the dipolar horizontal impedance of the ejection kicker (EK) of the PSB calculated when the kicker is matched at one side and open circuited at the other side and when the kicker is open circuited at both sides. The first resonance appears at 1.5 and 1.65 MHz. Anyway these values depend on cable length and characteristic impedance. The height and width of the peaks depend on the cable attenuation that is considered to be 0.1dB/m in the calculation.

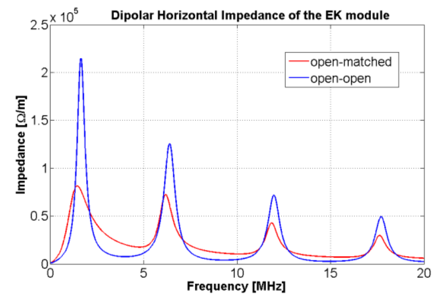

Figure 6: Driving horizontal impedance of the EK PSB kicker open terminated at both end (blue) and with one end matched and the other open terminated (red).

CONCLUSION

The EM problem of a device such a kicker magnet has been analyzed. A theoretical model based on the separation of the two different contributions to the coupling impedance (coupling with the magnet winding, TEM effect, and core losses) has been presented. The core losses contribution has been approximated with the Tsutsui model [1] while the TEM contribution for a C-Magnet was calculated using the same approach as in Ref. [4]. The model has been successfully benchmarked with CST-3D TD simulations and has been used to estimate the contribution of the external circuits for the EK PSB.

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