ELECTROMAGNETIC MODELING OF C SHAPE FERRITE LOADED KICKERS

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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 an intensity upgrade of the LHC. In this paper, analytical approach and CST Particle Studio time domain electromagnetic simulations are performed to obtain the longitudinal and transverse impedances/wake potentials of models of ferrite loaded kickers. It turns out that the existing models are not sufficient to characterize correctly these components from the coupling impedance point of view. In particular the results show that below few hundred MHz the real C-structure of the magnet cannot be neglected. Therefore an analytical model was developed and benchmarked with EM simulations to take into account the C-shape of the magnet.

ELECTROMAGNETIC MODELING

Presently the impedance contribution of the SPS kickers is taken into account using the Tsutsui model [1]. In this approximation the kicker consists of two parallel plates of ferrite. Despite of its simplicity the large detuning (also called quadrupolar) term of these kickers could explain both the "negative" total horizontal impedance observed in bench measurements [2] and the positive horizontal tune shift measured with the SPS beam [3].

However in this simple model several features of the kicker magnets have been neglected: hot and cold conductors at the sides of the aperture, C-shape magnetic yoke, cell longitudinal structure, transitions between the ferrite blocks and the SPS beam pipe, external circuits and geometry outside of the ferrite yoke.

Recent studies demonstrate that the connection between the two parallel plates of ferrite cannot be neglected below few hundred MHz. Therefore to estimate the kickers impedance contributions in this range of frequencies we need to resort to a C-Magnet or Frame-Magnet model (see Fig.1). For the ferrites 4A4 and 8C11 used in SPS kickers [4] the penetration depth was calculated (see Fig. 2). It is evident that below few hundreds of MHz the Tsutsui model cannot be applied: the penetration depth increases to several centimeters and becomes comparable with the distance between the two ferrite plates. Figure 3 consistent with what described, shows a simulation of the driving horizontal impedance. In this Figure we can clearly see that Tsutsui and C-Magnet or Frame-Magnet model are in perfect agreement above few hundreds of MHz but significantly differ below few hundred MHz. Similar results were obtained also for the detuning horizontal impedance [5]. A small impedance peak is also observed in the longitudinal and in the vertical impedances at the same frequencies [5]. The small peak in the longitudinal impedance was also observed in bench measurements for the MKP kickers [6].

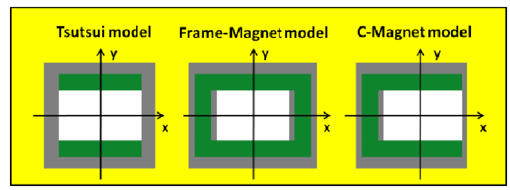

Figure 1: Geometric models for impedance calculation: ferrite in green, PEC in gray and vacuum in white.

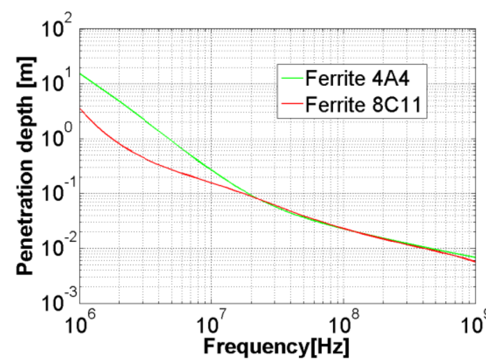

Figure 2: Penetration depth in ferrites 4A4 and 8C11.

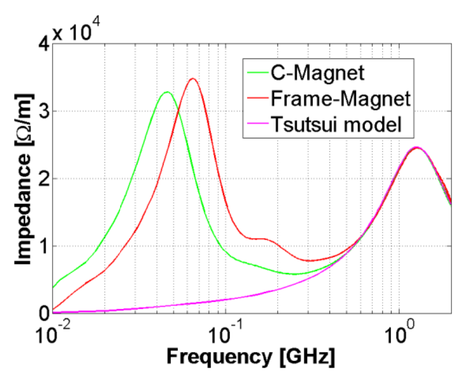

Figure 3: Simulations of the driving horizontal impedance for the MKP-L module using different models.

C-MAGNET IMPEDANCE

It is very interesting to calculate analytically the impedance contribution using the C-Magnet or the Frame-Magnet model. As first step we calculated analytically the impedance of a C-Magnet kicker without the High Voltage (HV) conductor approximating the kicker as shown in Fig. 4. From 3D time domain EM simulations we observed the consistence of the round approximation of a C-Magnet [7].

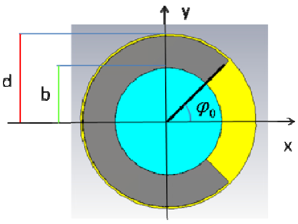

Figure 4: Geometric model for analytical derivation of the C-Magnet impedance: vacuum in light blue, ferrite in gray and PEC in yellow.

Analytical Approach

The model is indefinite in the longitudinal direction. The analysis is performed in FD and all the fields have the same behavior in the longitudinal direction. Using the Maxwell equations all the components of the fields are derived from the longitudinal fields of TE and TM modes. In vacuum EM fields are expanded in TE and TM cut-off waves expressed by modified Bessel functions of the first kind of integer order m:

$$E_z^v = Q\sum_m A_m I_m\left(\frac{k_0}{\beta\gamma} r\right) cos(m\varphi)$$

$$H_z^v = \frac{Q}{Z_0}\sum_m B_m I_m\left(\frac{k_0}{\beta\gamma} r\right) sin(m\varphi)$$

$$Q = j\frac{qk_0 Z_0}{2\pi\beta^2\gamma^2}$$

In ferrite EM fields are expanded in TE and TM progressive and regressive radial waves. They can be expressed by Bessel functions of non integer order v:

$$E_z^f = Q\sum_m C_m\left(J_\nu(k_+ r) - Y_\nu(k_+ r)\frac{J_\nu(k_+ d)}{Y_\nu(k_+ d)}\right) sin(\nu(\varphi - \varphi_0))$$

$$H_z^f = \frac{Q}{Z_F}\sum_m D_m\left(J_\nu(k_+ r) - Y_\nu(k_+ r)\frac{J_\nu'(k_+ d)}{Y_\nu'(k_+ d)}\right) cos(\nu(\varphi - \varphi_0))$$

$$\nu = \frac{\pi}{2\pi - 2\varphi_0}(2m+1)$$

$$k_+^2 = k_0^2\varepsilon_r\mu_r - \frac{k_0^2}{\beta^2}$$

The matching conditions are applied on the boundary between ferrite and vacuum by imposing the continuity of tangential fields and normal induction fields.

Resorting to the Ritz-Galerkin method, the functional equations are transformed into an infinite set of linear equations. We get the following system:

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\begin{pmatrix} A \\ B \end{pmatrix} = \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

where N_1 and N_2 are related to the sources. Then we write the following expressions of the unknown vectors:

$$B = \left[M_{22} - M_{21}M_{11}^{-1}M_{12}\right]^{-1}\left[N_2 - M_{21}M_{11}^{-1}N_1\right]$$

$$A = \left[M_{11} - M_{12}M_{22}^{-1}M_{21}\right]^{-1}\left[N_1 - M_{12}M_{22}^{-1}N_2\right]$$

where M_{12} and M_{21} can be rectangular with a ratio ν/m. By means of an ad-hoc truncation of matrices and vectors the system can be solved.

Impedance Derivation

The structure analyzed has no left/right symmetry. Therefore the transverse horizontal impedance is different from zero even when the beam passes in the geometric center. Thus beside the classical longitudinal and transverse (driving and detuning) impedance [8], also a so called constant term [9] must be derived.

Longitudinal Impedance

The source will consist in only one linear current placed on axis. We obtain the following expression of the source field:

$$E_z^s = QK_0\left(\frac{k_0 r}{\beta\gamma}\right)$$

and from E_z^v calculated in r=0 and φ=0 we get the classical longitudinal impedance for unit length:

$$\frac{Z_{//}}{L} = \frac{Q}{q}A_0$$

Driving Impedance

The source is a dipolar current of momentum p oriented in the horizontal direction:

$$E_z^S = Q_p\frac{k_0}{\beta\gamma}K_1\left(\frac{k_0 r}{\beta\gamma}\right) cos\,\varphi$$

The driving (also called dipolar) horizontal transverse impedance is then calculated as follow:

$$j\frac{Z_\perp}{L} = \frac{1}{p}\left[E_r^v - \beta Z_0 H_\varphi^v\right]_{\substack{r=0\\ \varphi=0}} = \frac{jQ_p}{2p\gamma}A_1$$

Detuning and Constant Impedance

The source is the same as for the longitudinal impedance. We obtain the following expressions respectively for detuning (also called quadrupolar) and constant horizontal impedance:

$$\frac{Z_\perp}{L} = \frac{Qk_0}{4q\beta\gamma^2}(A_0 + A_2)$$

$$\frac{Z_\perp}{L} = \frac{Q}{2q\gamma}A_1$$

Numerical Results

For one case (φ_0=π/4) we show all the impedances compared with the results obtained from the 3D EM code CST Particle Studio (see Figs. 5 and 6). The longitudinal impedance is normalized to the revolution frequency of the SPS. We can see that for all the impedances the analytical calculations show qualitatively the same behavior as the CST simulations with some quantitative differences (20-40% for the imaginary part and a shift to higher frequency for the peak on the real part). For the low frequency behavior we believe that the differences between simulations and analytical model could be due to the approximation of round structures with hexahedral meshes. For the high frequency behavior the difference has to be further investigated, but could be due to model limitations. However the goal of these studies is to investigate the "low frequency behavior" of these kickers. In the analytical model, even if much less intense, the low frequency peak of Fig. 3 is clearly visible.

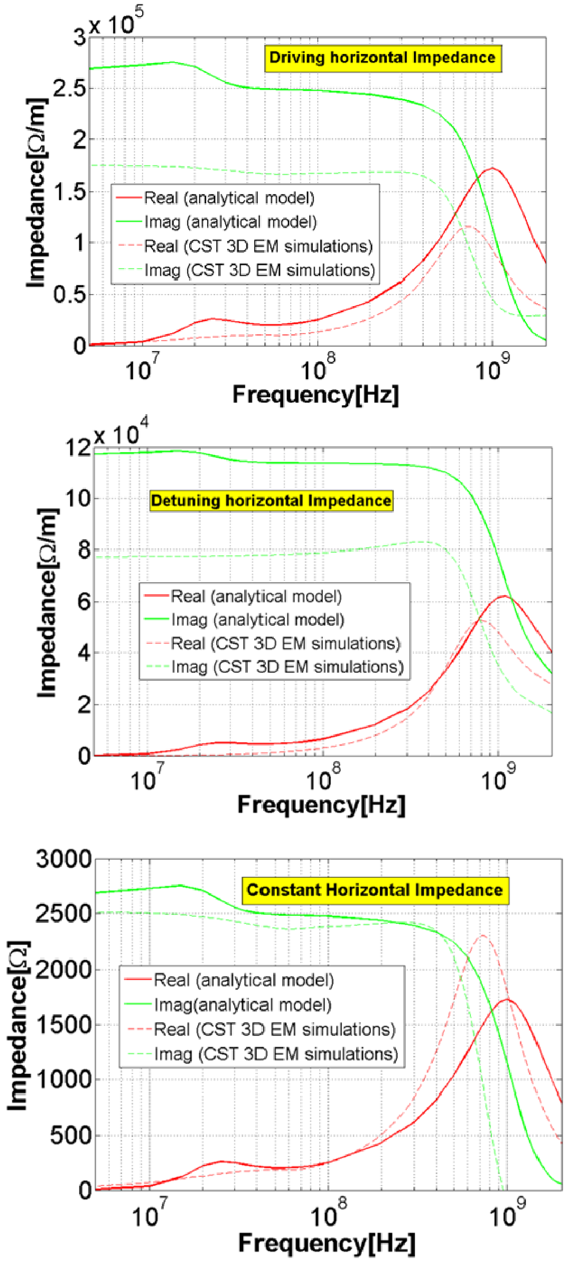

Figure 5: Comparison between the analytical model and CST 3D EM simulation for the horizontal transverse impedances (b=0.02 cm, d=0.04 cm, $\varphi_0=\pi/4$).

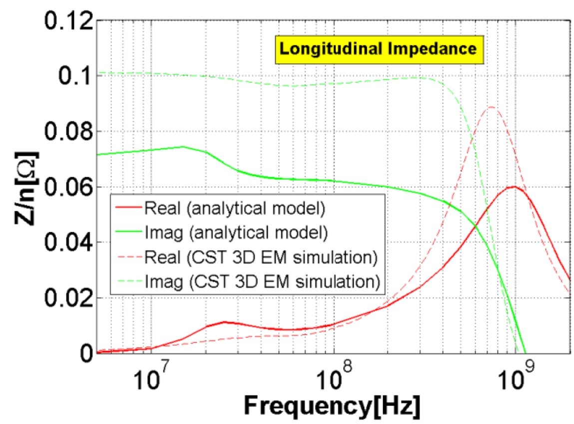

Figure 6: Comparison between the analytical model and CST 3D EM simulation for the longitudinal impedance (b=0.02 cm, d=0.04 cm, $\varphi_0=\pi/4$).

CONCLUSION AND OUTLOOK

We found that the connection of the two blocks of ferrite needs to be taken into account below few hundred MHz for the SPS kickers. Then a C-Magnet model or a Frame-Magnet model has to be considered. For these reasons we decided to develop an analytical approach for the C-magnet model. As future step we will improve the model of Fig. 4 adding the HV conductor and taking into account also the finite length of the magnet.

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