Transverse coupling impedance of a ferrite kicker magnet: Comparison between simulations and measurements *

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Abstract

The driving terms of instabilities in particle accelerators depend on the beam surroundings which are conveniently described by coupling impedances. In the case of critical components, for which analytical calculations are not available, direct measurements of the coupling impedances on a prototype are usually needed. However, this obvious drawback on the design of particle accelerators can be overcome by electromagnetic field simulations within the framework of the Finite Integration Technique (FIT). Here we show results from numerical evaluations of the transverse coupling impedance of a ferrite kicker. In order to excite the electromagnetic fields in the device we implement numerically the conventional twin-wire method. A good agreement with experimental measurement is observed, showing a promising way to determine coupling impedances of components of particle accelerators before construction.

INTRODUCTION

The electromagnetic interaction of an intensive charged particle beam with its vacuum chamber surroundings in an accelerator plays an important role for the beam dynamics and collective beam instabilities. Wakefields generated by a moving particle in the accelerator pipe and components affect the motion of particles in the tail part of the beam causing parasitic losses, beam energy spread, and instabilities. To avoid collective beam instabilities that limit the accelerator performance, an accurate numerical modeling of wake fields and their interaction with the beam is necessary.

In general, the behavior of wakefields and their action on the moving particles is rather complicated. Hence, the notion of the coupling impedance is used to estimate wakefield effects. In fact, the coupling impedance describes the response of an accelerator chamber component to a bunch of electrical particles, which is described by a Dirac delta function. Coupling impedances are independent of the beam properties and defined totally by properties of the accelerator chamber component [1, 2].

In order to calculate the coupling impedance of a accelerator component, the value of the Lorentz force acting on the moving particles due to the wakefields has to be calculated. In particular, the transverse components of this force are critical for the stability of the beam, since they can drive the particles out of their optimal path, i.e. the main axis of symmetry of the system. This unwanted effect can be estimated by means of the transverse coupling impedance [1], i.e.

$$\mathbf{Z}_{\perp} = \frac{i}{q\,P}\int_{-\infty}^{\infty} dz \mathbf{F}_{\perp}(\mathbf{r},\omega)\exp\left(i\omega\, z/v\right), \qquad (1)$$

where, $\mathbf{F}_{\perp}(\mathbf{r},\omega) = q[\mathbf{E}_{\perp}(\mathbf{r},\omega) + (\mathbf{v}\times\mathbf{B}(\mathbf{r},\omega))_{\perp}]$ is the transverse Lorentz force generated by the transverse electric field $\mathbf{E}_{\perp}$ and the magnetic field $\mathbf{B}$. P is the transverse moment of the charge $q\,\mathbf{r}_{\perp}$, where $\mathbf{r}_{\perp}$ is the transverse component of $\mathbf{r}$. Here, the particles are moving with a constant velocity $\mathbf{v} = \beta c\hat{z}$ along the main axis of symmetry of the system.

Notice that low values of $\mathbf{Z}_{\perp}$ are required for the normal operation of a particle accelerator. In the case of the Spallation Neutron Source (SNS) accumulator ring [3], the ferrite kicker magnet [4, 5] has represented the most critical impedance among the component devices. This device is a window frame magnet used to deflect the beam vertically by means of a pulsed magnetic field. The transverse coupling impedance of this kicker magnet was intensively studied [4, 5] by using the twin-wire method. Since the dimensions and materials of the kicker as well as measurements and measurement methods are well documented, this kicker is a suitable system to be simulated to compute transverse coupling impedances for benchmarking.

In the present paper we consider the numerical calculation of the vertical coupling impedance of the SNS ferrite kicker magnet, which is schematically illustrated in Fig. 1. For that full electromagnetic field simulation of the device in consideration is performed, where the fields are excited by a dipole current source. We show that the metallic frame fastening the window frame magnet has to be taken into account in order to make quantitative estimations of the vertical coupling impedance of the system. Comparison with reported measurement [4, 5] are performed showing a good agreement.

TRANSVERSE IMPEDANCE AND CURRENT SOURCE

The transverse impedance in the y direction, which is known as the vertical impedance Z_y, is one of the two components of Eq. (1). Z_y has finite value for moving leading particles displaced some small distance Δy in the y direc-

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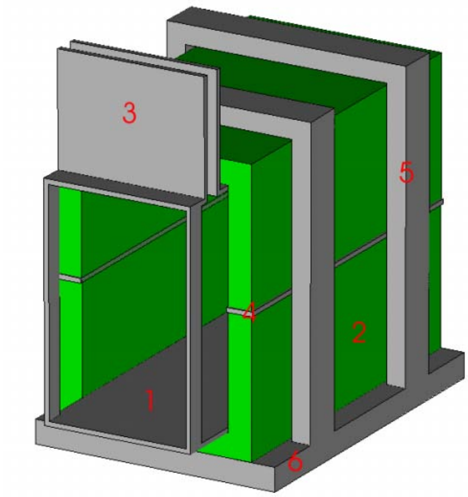

Figure 1: Schematic view of the SNS kicker where it is possible to observe the busbar (1), the ferrite (2), the end-plates of the busbar (3), the strips (4), a frame (5) and a base (6).

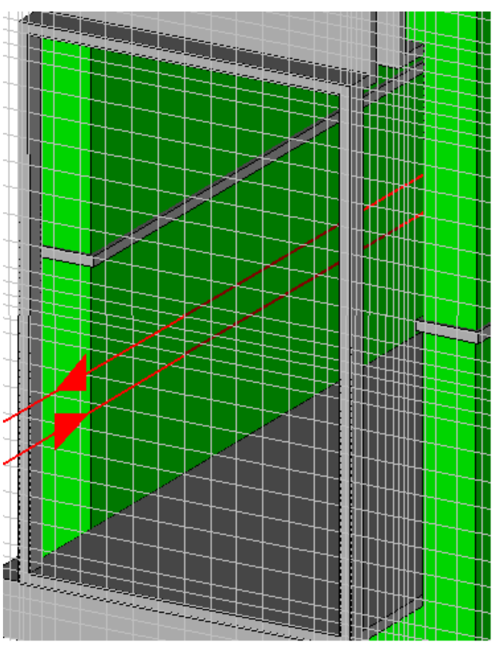

Figure 2: Schematic view of the SNS kicker where it is possible to observe the position and direction of the dipolar current.

tion from its optimal path. In most of the cases this optimal path is located exactly on the main axis of symmetry of the system, which for convenience here is chosen to be the z axis of the coordinate system. By using Faraday's law Z_y can be reduced to the form [6]

$$Z_y = -\frac{1}{k\,P}\int_{-\infty}^{\infty} dz\partial_y E_z(\mathbf{r},k)\exp\left(i\,k\,z\right)\Big|_{\mathbf{r}=(0,0,z)}, \quad (2)$$

where E_z is the component of the electrical field in the z direction, $k = w/(\beta\, c)$ is the wavelength number, and $\mathbf{r} = (0, 0, z)$. The other component of the transverse coupling impedance in Eq. (1), namely the horizontal impedance Z_x, has a similar representation. For numerical purposes it is convenient to rewrite Eq. (2) as

$$Z_y = -\frac{1}{2\,\omega\,P^2}\int d^3\mathbf{r} E_z(\mathbf{r},k) j^*(\mathbf{r},k), \quad (3)$$

where

$$j(\mathbf{r},k) = qv(\delta(y+\Delta y) - \delta(y-\Delta y))\delta(x)\exp\left(-i\,k\,z\right), \quad (4)$$

with δ as the Dirac delta function. In order to obtain Eq. (3) the definition of central differences for the term $\partial_y E_z$ was used [6].

Since our interest here is to compute the transverse impedances, which is calculated only from the transverse components of the Lorentz force, the longitudinal component can be suppressed. This can be done in theory by considering a second leading particle with opposite charge sign moving parallel with the first leading particle but displaced $-\Delta y$ with respect to the axis of symmetry. Under these conditions these two leading particles, which can be modeled as a dipolar density current equal to that shown in Eq. (4), excite only the vertical Lorentz force. Notice that a factor 1/2 has to be introduced to preserve the magnitude of the vertical impedance. So, finally, the vertical coupling impedance reads

$$Z_y = -\frac{1}{4\,\omega\,P^2}\int d^3\mathbf{r} E_z^{(2)}(\mathbf{r},k) j^*(\mathbf{r},k), \quad (5)$$

where $E_z^{(2)}$ is the electrical field in the z direction excited by the dipolar density current. We note that a similar formula can be derived for the horizontal impedance Z_x. On the other hand, the experimental realization of the dipolar density current given in (4) is known as the two-wire method for measuring transverse impedances [4, 5].

NUMERICAL SOLUTION OF THE MAXWELL EQUATIONS

The main task in computing either Z_x, or Z_y is to solve Maxwell's equations in frequency domain with the excitation density current given by Eq. (4). Usually, from the Maxwell equations one can eliminate the magnetic field by combining the equations. So, one gets at the end the well known curl-curl equation,

$$\boldsymbol{\partial}\times\mu^{-1}\boldsymbol{\partial}\times\mathbf{E} - \omega^2\epsilon\mathbf{E} = -i\omega\mathbf{j} \quad (6)$$

with $\mathbf{j} = j(\mathbf{r},k)\hat{z}$, where $j(\mathbf{r},k)$ given by Eq. (4). Here, ϵ and μ are the permittivity and permeability, respectively, of the medium. We have solved Eq. (6) within the FIT framework , first proposed in [7].

We have used Eq. (5) to calculate Z_y numerically. Notice that in order to simulate the dipolar density current

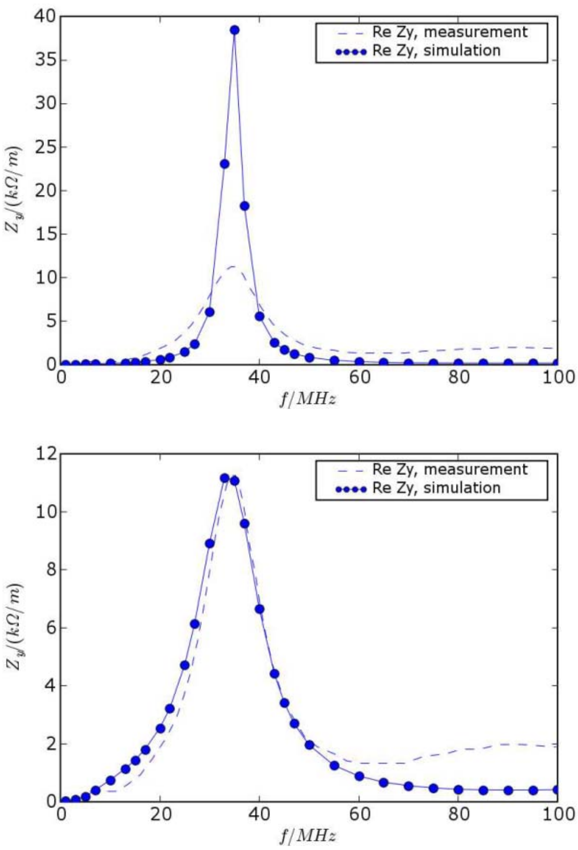

Figure 3: Z_y vs. frequency for the case $Z_{ext} = \infty$. The dotted line follows from simulation and dashed line from experimental measurements[4, 5].

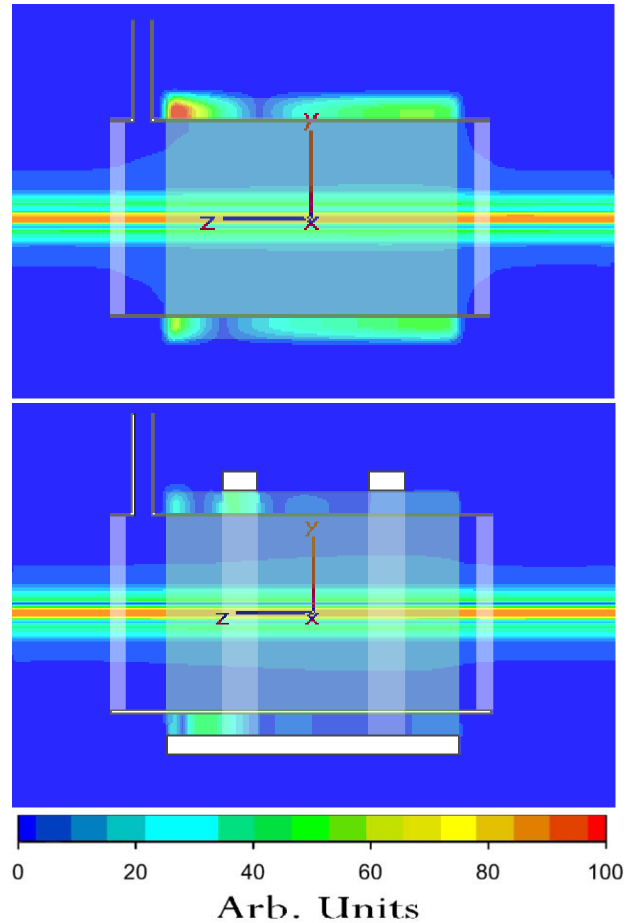

Figure 4: Vertical cutting plane at x=0 of the kicker magnet without (upper panel) and with (lower panel) the metallic frame showing contour plot of $|B_x|$ for $f = 35$ MHz.

$j(\mathbf{r}, k)$ two wires with opposite currents have to be inserted into the kicker magnet, as shown in Fig. 2.

Constructing the computational models, meshing, and visualization of calculated fields has been done with the commercial program CST MICROWAVE STUDIO (R) [8]. Further details on the simulations are given in Ref. [9] and references therein.

THE FERRITE KICKER MAGNET

In References [4, 5] it is given a detailed description of the SNS kicker as well as the experimental two-wire method for measuring transverse impedances. Moreover, an analytical model was provided [4] showing a good agreement with experimental results. In Fig. 1 we show an schematic view of the kicker. In particular, it is possible to see a metallic busbar, i.e. two metallic sheets, inserted in a ferrite frame, which in turn is fastened by a stainless steel frame and a base. The busbar has two end plates in a vertical position, which provide a connection to a feedthrough, where the external impedances are connected. Notice that these end-plates form a capacitor, which leads to resonant behavior of the kicker. The ferrite type is CMD5005 [10], which is Nickel Zinc (NiZn) ferrite with the initial real permeability of 2600 at low frequency [11]. Notice that this is a high permeability value, which implies low effective resistor in parallel with the magnet inductance [11]. In general, the permeability of ferrites is complex and contributes to the formation of eddy currents and hysteresis losses. In order to reduce these effects eddy current stripes are inserted in the ferrite loop as shown in Fig. 1. In the case of the ferrite CMD5005 the log-log behavior of the real and imaginary part of the permeability in the region between 1 and 100 MHz is rather smooth [11], which facilitates its interpolation during simulations. Dimension of the kicker magnet are reported in Refs. [4, 5, 12] and references therein.

RESULTS

Since large values of the transverse coupling impedance lead to a beam instability in the particle accelerator, it is very important to reduce them. We note that in the theory one could reduce the values of the transverse impedance by increasing the aperture window of the kicker magnet. But usually it is impracticable. The other way to reduce the transverse coupling impedance is to connect an external impedance, Z_{ext}, to the feed-through located on the end-plates of the busbar (see Fig. 1) [4, 5]. In fact, in the low-frequency regime ($f < 100$ MHz) the kicker magnet can be seen as a RLC parallel circuit, where R, L and C represent the losses, inductance and capacitance of the system. In this representation an external impedance is seen also in parallel to this circuit and therefore contributing to the reduction of the total impedance. Since the goal of the present article is to study the effect of the metallic frame fastening the window magnet, we do not consider the contribution of any external impedance, i.e. $Z_{ext} = \infty$. Indeed, finite external impedances connected to the kicker end-plates reduces the vertical impedance and therefore masks any frame effect on the vertical impedance.

We first consider the case of the kicker without the metallic frame. The motivation behind this case study is that in Ref. [4] a simple analytical model was developed from this simplified system in order to estimate vertical coupling impedance. In Fig. 3 upper panel shows a comparison of Z_y between simulations and experimental measurements [4]. We observe that the resonance at $f = 35$ MHz is predicted correctly, However the amplitude of the vertical impedance following from simulations is about three times larger. So, this shows that the simplified model can not describe quantitatively well the impedance behavior of the system. Therefore a more detailed description of the system is considered in which the metallic frame is present. In Fig. 3 lower panel it is shown the transverse impedance for this latter case. We observe that in general the impedance is well described for frequencies below 60 MHz. For higher frequencies a discrepancy is observed which is mostly due to experimental problems of the two-wire method as discussed in Ref. [5].

In order to understand the effect of the metallic frame on the transverse impedance we show in Fig. 4 a vertical cutting plane of the system at x=0 showing the contour plot of the absolute value of the horizontal component of the magnetic field, $|B_x|$, for both cases at the resonance frequency. We observe that $|B_x|$ concentrates mainly in the z-axis as well as in the ferrite region. We observe that the distribution of $|B_x|$ along the z-axis is uniform. It is because the dipolar density current flows along this axis. On the other hand, the distribution of $|B_x|$ in the ferrite region is not uniform, being the concentration higher in the extremity close to the capacitor. We observe also that concentration of $|B_x|$ is higher in the ferrite when the metallic frame is absent. We note that most of the magnetic flux lines are pushed out of the regions close to metal boundary. It is because the magnetic field is excluded from the interior of a metal region, which here is modeled as a perfect electric conductor (PEC). So, the magnetic field must decay to zero in the boundary with the PEC region. In particular, the expulsion of many magnetic flux lines from the ferrite region reduces the energy dissipation in the system, since these lines are pushed to the vacuum region, where no losses are present. This overall effect is reflected in the reduction of the vertical impedance as we observe in Fig. 3.

CONCLUSIONS

We have simulated numerically the two-wire method for the estimation of transverse coupling impedances in accelerator components. For that we have computed the electromagnetic fields excited by dipolar density current simulating the two wires which are inserted into the device under test. We have solved numerically the curl-curl equation in the frequency domain by using Finite Integration Technique. We have considered as example model the SNS ferrite kicker magnet which has been intensively studied in several papers. In this specific example we have considered two cases in order to study the effect of a metallic frame fastening the ferrite kicker magnet. We have shown that this frame contribute significantly to reduce the total vertical coupling impedance of the system. Good agreement with experimental results have been obtained. We have also shown that a detailed numerical model is needed in order to describe correctly the behavior of the system.

REFERENCES

[1] B. W. Zotter, S. A. Kheifets, " Impedances and Wakes in High Energy Particle Accelerators", World Scientific, Singapore (1998).

[2] A. Chao, M. Tigner, "Handbook of Accelerator Physics and Engineering", World Scientific, Singapore (1999).

[3] J. Wei et al.," Low-loss design for the high-intensity accumulator ring of the Spallation Neutron Source" Phys. Rev. ST Accel. Beams 3 (2000) 080101.

[4] D. Davino and H. Hahn, "Improved analytical model of the transverse coupling impedance of ferrite kicker magnets", Phys. Rev. ST Accel. Beams 6 (2003) 012001.

[5] H. Hahn, "Impedance measurements of the Spallation Neutron Source extraction kicker system", Phys. Rev. ST Accel. Beams 7 (2004) 103501.

[6] R. L. Gluckstern, "Analytic methods for calculating coupling impedances", CERN-2000-011 (2000).

[7] T. Weiland, "Discrete electromagnetics with the Finite Integration Technique", AEU-Int. J. Electron. Commun. 31 (1977) 116.

[8] CST GmbH. Bad Nauheimer Str. 19, 64289 Darmstadt.

[9] B. Doliwa, H. De Gersem, and T. Weiland "Numerical calculation of coupling impedances for kicker modules", FAIR (Facility for Antiproton and Ion Reserch) report (2006).

[10] Ceramic Magnetics Inc., Fairfield, NJ.

[11] S. Y. Zhang, "Resonance Model of ferrite assembly for window frame magnet kicker impedance" C-A/AP/20 (2000).

[12] H. Hahn and D. Davino, private communication (2006).