NUMERICAL CALCULATION OF COUPLING IMPEDANCES FOR KICKER MODULES*

B. Doliwa**, H. De Gersem, T. Weiland, Technische Universitaet Darmstadt, Institut fuer Theorie Elektromagnetischer Felder, Schlossgartenstrasse 8, 64289 Darmstadt, Germany

Abstract

Maintaining the impedance budget is an important task in the planning of any new accelerator facility. While estimates from analytical computations and measurements play a central role in doing so, numerical calculations have become an important alternative today. On the basis of the Finite Integration Technique, we have developed a simulation tool for the direct computation of coupling impedances in frequency domain. After discussing the special features of our code as compared to commercial programs, we present results for the transverse and longitudinal coupling impedances of the SNS extraction kicker and the injection/extraction system of the heavy-ion synchrotron SIS-18 at GSI.

INTRODUCTION

At the Gesellschaft für Schwerionenforschung in Darmstadt (GSI), an ambitious extension of the existing heavy-ion accelerator facility is currently undertaken. An essential goal is to reach high ion currents with simultaneous small momentum spread, e.g., up to 10^{12} U^{28+} particles per bunch, with $\delta_p < 10^{-3}$. The effort to obtain a stable ion beam of this quality is considerable: besides the required vacuum pressure of ca. 5×10^{-12} mbar, detailed beam dynamics studies are aiming at optimizing critical parts of the existing and the planned parts of the accelerator. The motivation behind the work presented here is that the beam response to the injection/extraction kickers is one of the important unknowns in the machine impedance budget.

As is well known [1], the interaction of a nearly rigid particle beam with the surrounding accelerator components can efficiently be described by the coupling impedance. In this work, we use the common definitions of its transverse and longitudinal parts,

$$Z_{x,y}(\omega) = -\frac{\beta c}{\omega \Delta^2} \frac{1}{q^2} \int \mathrm{d}^3 x \boldsymbol{J}^*_{x,y} \cdot \boldsymbol{E}.$$

$$Z_{||}(\omega) = -\frac{1}{q^2} \int \mathrm{d}^3 x \boldsymbol{J}^*_{||} \cdot \boldsymbol{E}$$

with the corresponding beam currents,

$$\boldsymbol{J}_x(x,y,z;\omega) = q\hat{z}\left(\delta(x-\frac{\Delta}{2}) - \delta(x+\frac{\Delta}{2})\right)\delta(y)e^{-\mathrm{i}kz},$$

$$\boldsymbol{J}_y(x,y,z;\omega) = q\hat{z}\delta(x)\left(\delta(y-\frac{\Delta}{2}) - \delta(y+\frac{\Delta}{2})\right)e^{-\mathrm{i}kz}.$$

$$\boldsymbol{J}_{||}(x,y,z;\omega) = q\hat{z}\delta(x)\delta(y)e^{-\mathrm{i}kz}.$$

Note that $\boldsymbol{J}_{||}$ is the fourier transform of a point particle travelling with velocity $\beta c = \omega/k$ along the positive z direction, whereas $\boldsymbol{J}_x$ and $\boldsymbol{J}_y$ each describe two currents of opposite directions. We further remark that the above expression for $Z_{x,y}$ is an approximation valid for small transverse displacements Δ, see [1] for details.

Many examples of kicker impedance measurements can be found in the literature [2, 3, 4, 5]. The main idea behind these experiments is to mimic the beam by two parallel wires, an idea going back to Nassibian and Sacherer [6], short, NS. With the help of a network analyzer one determines the impedance of the twin-wire loop and calculates the transverse coupling impedance by scaling the twin-wire impedance by $\beta c/\omega\Delta^2$. This experimental approach seems to yield reliable results, although a good deal of experience and measurement art appears to be involved. The obvious drawback, however, is that a prototype component has to be at hand. Furthermore, impedances are determined with the kicker 'on the bench', i.e. under possibly different conditions than that of the mounted device.

In this light, numerical electromagnetic field calculations seem to be an important supplementary approach, especially during the design process of new components. In particular, the access to the full 3D field information may open new ways of optimization.

We will first discuss the status of our simulation code before reporting the results for the SNS extraction kicker and the SIS-18 kicker at GSI.

COMPUTATIONAL APPROACH

The main task is to compute the electromagnetic fields due to the excitations $\boldsymbol{J}_{x,y,||}$ inside the accelerator component, which we accomplish within the framework of the Finite Integration Technique [7]. After spatial discretization, we obtain a matrix counterpart of the continous wave equation,

$$\tilde{\boldsymbol{C}} M_\nu \boldsymbol{C} \boldsymbol{e} - \omega^2 M_\epsilon \boldsymbol{e} = -\mathrm{i}\omega \boldsymbol{j}_{\text{ext}}. \quad (1)$$

Here, $\tilde{\boldsymbol{C}}$ and $\boldsymbol{C}$ represent discrete curl operators, M_ϵ and M_ν reflect permittivity and inverse permeability, while $\boldsymbol{j}_{\text{ext}}$ stands for either of the $\boldsymbol{J}_{x,y,||}$. The solution of matrix Eq. 1 is the discrete electric field vector $\boldsymbol{e}(\omega)$.

In the following we will discuss two complications that make Eq. 1 non-trivial to solve. Firstly, the presence

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** doliwa@temf.tu-darmstadt.de

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of ferrites in the kicker results in a complex, frequency-dependent inverse permeability matrix, which exhibits large variations between its entries ($\mu_{\text{air}} = 1, |\mu_{\text{ferrite}}| > 1000$). As a consequence, the matrix equation becomes highly ill-conditioned. To overcome this computational bottleneck we have developed an optimized low-frequency solver that treats the term $\omega^2 M_\epsilon$ as a perturbation and uses powerful solution strategies from magnetostatics.

The second complication arises from the definition of the beam currents $\boldsymbol{J}_{x,y,||}$, which, obviously, extend across the end of the accelerator component under investigation. Generally, the transitions from the beam pipe to the module have to be included into the computation, since jumps in pipe cross sections contribute to the coupling impedance. For frequencies below beam-pipe cutoff, the fields excited within the module decay exponentially along the beam pipe. Thus, at some distance along the beam pipe, the perturbation resulting from the module can be neglected and fields can be considered stationary in the sense that $(\boldsymbol{E}, \boldsymbol{B})_{\text{pipe}} \propto \exp(-ikz)$. Using this property, we set up boundary conditions for the 3D problem by solving for $(\boldsymbol{E}, \boldsymbol{B})_{\text{pipe}}$ in a 2D cross section of the beam pipe. For a complete treatment of beam-adapted boundary conditions, see [8].

We finally remark that the modelling and discretization are carried out in CST MicroWave Studio [9] whereas the simulation itself relies upon an own implementation in MATLAB [10].

SNS EXTRACTION KICKER

Recently, Hahn and coworkers have performed detailed measurements at a prototype of one of the 14 SNS extraction kickers. In a series of papers (e.g. [4, 5]), they have investigated the transverse coupling impedances of the window-frame magnet under different magnet terminations, Z_g. This gives us the opportunity to check our numerical results against their wire measurements.

We have used a model of the kicker prototype following the description in [4]. The frequency dependence of the ferrite permeability (CMD5005) has been obtained from the supplier's data sheet (Ceramic Magnetics Inc., Fairfield, NJ), whereas we have taken $\epsilon_{\text{CMD5005}} = 12$, see [11].

In Fig. 1, top, we compare the numerical results for the horizontal impedance with measurement. The simulated impedance exhibits a constant imaginary part (corresponding to the inductance of the twin-wire loop) and an approximately linear real part stemming from the losses inside the ferrite. The agreement with the experimentally observed $Z_x(\omega)$ is not completely satisfactory, even when taking into account the maximum expected error bars. It is a matter of further research to resolve this discrepancy.

Figure 1, bottom, shows the longitudinal part of the impedance, for which, unfortunately, no experimental data are available for comparison.

For reasons of brevity we skip the subjects of the longitudinal impedance of a displaced beam and of the vertical

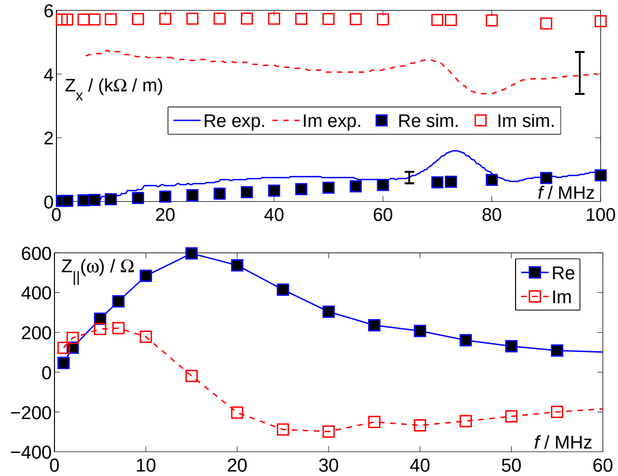

Figure 1: Top: horizontal coupling impedance of the SNS kicker prototype for $\beta = 1$. Experimental data are taken from [4]. We have added error bars for the expected maximum measurement error. Bottom: longitudinal coupling impedance, determined by simulation.

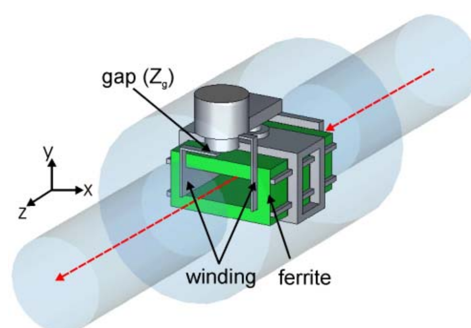

Figure 2: Model of the SIS-18 kicker magnet at GSI, with aperture height 6 cm, width 16 cm, length of magnet 25 cm. The total length of the model is 150 cm, radius of the vacuum vessel 20 cm, beam-pipe radius 10 cm. Grey parts are perfectly conducting. The ferrite material is 8C11 (*www.ferroxcube.com*).

impedance. After [6], both quantities are expected to be dominated by the inductive coupling to the magnet winding and the external network. We will discuss this issue in a separate work.

SIS-18 KICKER

We now turn to the model of the SIS-18 kicker, as displayed in Fig. 2. Experimental results for this device have been reported by Blell [3]: after measuring the impedance of the pulse-forming network ($Z_g(\omega)$) and the magnet inductance ($L \approx 1.36\mu$H), he estimated the transverse coupling impedance in -horizontal- kick direction via the NS approach, i.e.

$$Z_{x,\text{NS}}(\omega) = \frac{\beta c \omega \mu_0^2 l^2}{4a^2 Z_k}, \qquad (2)$$

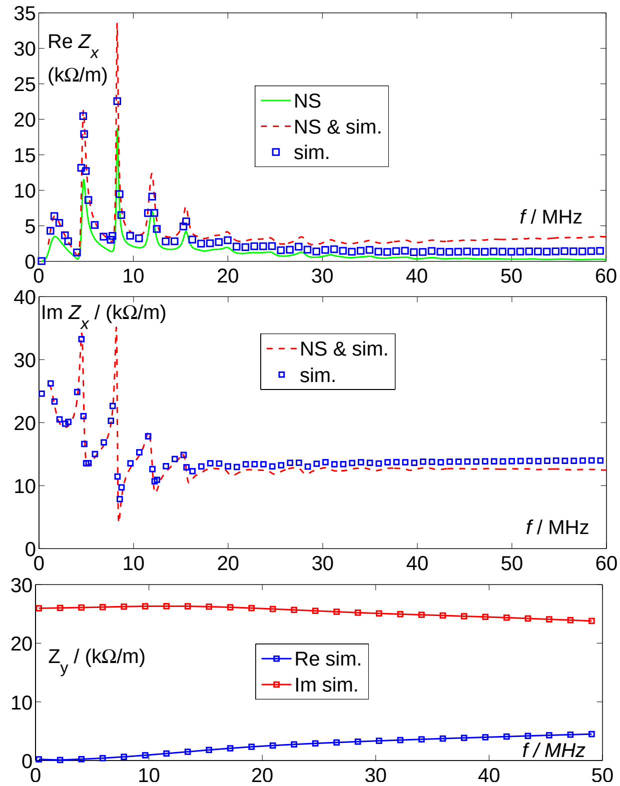

Figure 3: Horizontal (x) and vertical (y) impedances for the model of Fig. 2 at $\beta = 0.85$. Curves 'NS' follow directly from the measurements of Blell and Eq. 2, 'NS&sim.' corresponds to a numerical correction of Eq. 2, and 'sim.' means direct simulation, see text.

where $Z_k = Z_g + \mathrm{i}\omega L$, $2a$ is the aperture width, and l the magnet length. This quantity is shown in Fig. 3, top (NS).

Numerically, the network impedance $Z_g(\omega)$ has been implemented directly by modifying the material matrix M_ϵ on a path of grid edges between the terminations of the magnet winding (see Fig. 2). Consequently, the displaced beam inductively couples to the total magnet impedance Z_k. The results for Z_x can be seen in Fig. 3 ('sim.').

The deviation of Re Z_x from the results by Blell can be attributed to two effects: Firstly, the influence of the ferrite is not included in Eq. 2. Secondly, the underlying analytical value for the mutual inductance between magnet winding and beam, M, is only approximately correct.

Interestingly, the NS transformator approach becomes more useful when combined with simulations: it is possible to determine the contribution from the ferrite ($Z_{\text{x,ferrite}}$, data not shown here) in a separate computation with $Z_g = 0$, a fact that has recently been observed in [4]. Moreover, the NS approximation for M can be replaced by the result from a 3D field simulation. This leads to the expression $Z_x = \beta c\omega M^2/\Delta^2 Z_k + Z_{\text{x,ferrite}}$, instead of Eq. 2. As shown in Fig. 3, curves 'NS&sim', we find a much better agreement with the direct simulation results below ca. 20 MHz. Above this frequency, the present parameterization breaks down for Re Z_x, an effect which deserves further investigation.

We finally observe that the vertical impedance, Z_y, does not sense the external network, due to the lack of inductive coupling (Fig. 3, bottom).

CONCLUSION

The reported results demonstrate the feasibility of numerical coupling impedance calculations for kicker modules. The comparison we have made with experiment suggests that consistency with simulations is achievable, but that possibly further refinements of our model systems may be needed. As an example, we remark that the eddy-current strips, missing in our model of the SNS kicker so far, should provide noticeable corrections to the data of Fig. 1.

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