NUMERICAL IMPEDANCE CALCULATIONS FOR THE GSI SIS-100/300 KICKERS*

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Abstract

Fast kicker modules represent a potential source for beam instabilities in the planned Facility for Antiproton and Ion Research (FAIR) at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt. In particular, the more than forty kicker modules to be installed in the SIS-100 and SIS-300 synchrotrons are expected to have a considerable parasitic influence on the high-current beam dynamics. Here we present our numerical investigations of the longitudinal and transverse kicker coupling impedances using a specialized electromagnetic field software. Besides the coupling to the external network, particular attention is paid to the question whether a resistively-coated ceramic beam pipe is able to reduce coupling impedances and ferrite heating significantly.

INTRODUCTION

Ensuring the stability of high-intensity ion beams is one of the most important research and development goals within the design work of the planned Facility for Antiproton and Ion Research (FAIR) at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt. Currently, detailed beam dynamics studies are aiming at optimizing critical parts of the existing and the planned parts of the accelerator.

Containing more than six tons of lossy ferrite material, the various fast kicker devices of the SIS-100/SIS-300 synchrotrons (injection, extraction/emergency, transfer, and Q kickers) are expected to have a significant contribution to the overall machine impedance. The design of the kicker devices, therefore, has to take into account their parasitic influence on beam stability. As we have demonstrated in previous publications [1, 2], numerical field calculations offer a convenient way of providing coupling impedance data without the need of protoypes.

Here, for brevity, we report our numerical results on the window-frame SIS-100 injection device only. Details about the computational approach can be found in [1, 2] along with the used definitions of the longitudinal ($Z_{||}$), horizontal (Z_x), and vertical (Z_y) impedances. We merely remark that the modelling and discretization are carried out in CST MicroWave Studio [3], whereas the simulation itself relies upon an own implementation in Python [4] and C++, using the linear-algebra facilities of the Trilinos library [5].

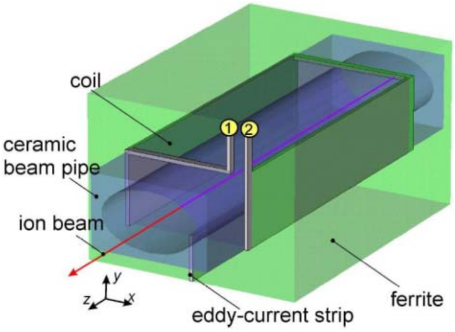

Figure 1: Model of one module of the window-frame SIS-100 injection kicker, with aperture height 10 cm, width 17.5 cm, length of module $L = 40$ cm, thickness of ferrite plates 6 cm. The ceramic beam pipe is of elliptical cross section (width 13.5 cm, height 8 cm, $\epsilon_r = 9.6$). A so-called eddy-current strip has been added to the model in order to reduce $Z_{||}$ and Z_y. Metal parts and model boundary are assumed to be perfectly conducting. The ferrite material is 8C11 (*www.ferroxcube.com*). The pulse-forming network (PFN) is represented by a lumped impedance, Z_{PFN}, applied between 'plugs' (1) and (2).

THE SIS-100 INJECTION KICKER

We consider the model of the SIS-100 injection kicker as displayed in Fig. 1. Due to outgassing at the low vacuum pressures the ferrite parts need to be placed outside of the ultra-high vacuum. Inside the magnet, a ceramic beam pipe piece is used, which, as planned in an early design stage, is coated by a thin metal layer (of e.g. titanium). The purpose of this kind of coating is to shield the magnet from the beam-induced electromagnetic fields, thus reducing the energy deposited within the ferrite parts (ferrite heating) as well as coupling impedances [6]. However, besides increased production costs, a shortcoming of the metallization is that it may damp the rise of the kick field. It is therefore natural to first check whether the kicker design without metal shielding is sufficient.

In [2], we have shown that a so-called eddy-current strip (see Fig. 1) reduces the energy deposition in the ferrite by more than a factor of twenty, thus solving the problem of ferrite heating in the SIS-100 injection kicker.

Here we report our results for the horizontal coupling impedance, $Z_x(\omega)$. As already pointed out by Nassibian and Sacherer (NS), Z_x is dominated by the inductive coupling of the beam to the pulse-forming network (PFN), represented by a lumped impedance $Z_{\text{PFN}}(\omega)$. In their seminal

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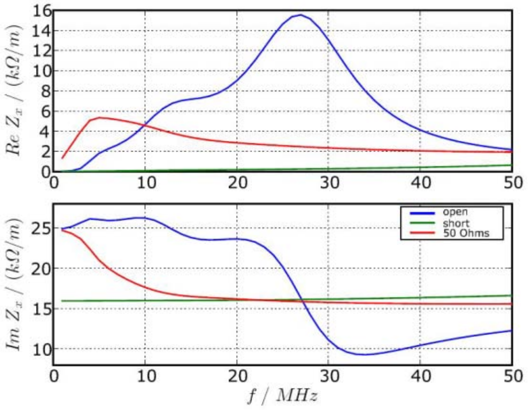

Figure 2: Horizontal impedances for the model of Fig. 1 at beam velocity $\beta = v/c = 1$. Three different lumped PFN impedances have been used, see text. Top: real part, bottom: imaginary part.

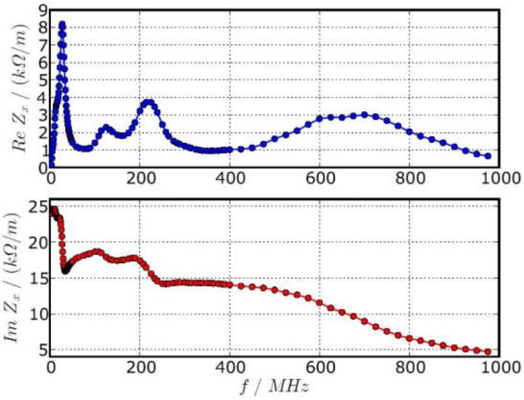

Figure 3: $Z_x(\omega)$ for $Z_{\text{PFN}} = \infty$ (open termination), $\beta = 0.5$, for a larger frequency range. Top: real part, bottom: imaginary part.

paper [7], they developed a simple transformer picture, in which beam and kicker magnet winding consitute the (virtual) primary, and the secondary coil, respectively. In a recent technical report [2], we went one step further into this direction and proposed a parameterized model describing the effect of an arbitrary PFN impedance on the horizontal coupling impedance, taking into account an additional intrinsic impedance parallel to the PFN. The parameterization reads,

$$Z_x(\omega, Z_{\text{PFN}}(\omega)) = \frac{A(\omega)Z_{\text{PFN}}(\omega) + B(\omega)}{Z_{\text{PFN}}(\omega) + C(\omega)}, \tag{1}$$

with parameters A, B, and C. The latter are determined by three frequency sweeps with different Z_{PFN}, where, for simplicity, we use $Z_{\text{PFN}} \in \{0, 50, \infty\}\ \Omega$, see Fig. 2. In Fig. 3, Z_x (open termination) is displayed for a wider frequency range.The actual PFN to be used in connection with the SIS-100 injection kicker is identical to the SIS-18-kicker PFN, for which Blell has reported the corresponding equivalent lumped resistance $Z_{\text{Blell}}(\omega)$ [8]. In order to demonstrate the accuracy of the parameterized model, we have computed $Z_x(\omega)$ in two ways: Firstly, by applying Z_{Blell} directly in the electromagnetic field calculation (see Fig. 1), secondly by using $Z_{\text{PFN}} = Z_{\text{Blell}}$ in Eq. 1. Figure 4 shows an excellent agreement between these two approaches. For comparison, we have added the prediction of the NS transformer model.

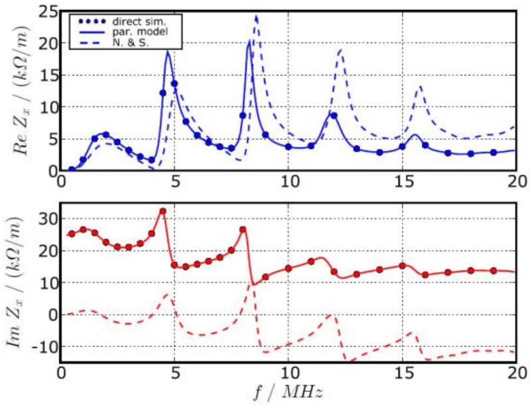

Figure 4: Comparison of $Z_x(\omega)$, $\beta = 1$, obtained directly from simulation, with the prediction of the parameterized model, Eq. 1. The dashed line corresponds to the NS transformer model. Top: real part, bottom: imaginary part.

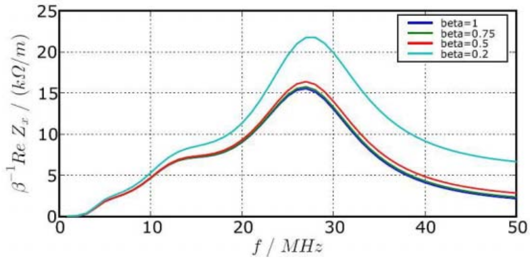

Figure 5: Real part of $\beta^{-1}Z_x(\omega)$ for open PFN termination (i.e., $Z_{\text{PFN}} = \infty$) at different beam velocities $\beta = v/c$.

We next consider the influence of the particle velocity, $v = \beta/c$ on the transverse coupling impedance. As implied by its definition [1], $Z_x(\omega) \propto \beta$ for small ω. Since the excitation current is $\propto \exp(-\mathrm{i}kz)$, where $k = \omega/\beta c$, the scaling $Z_x \propto \beta$ is expected as long as $kL \ll 1$, where L is the length of the kicker module. This behavior is checked in Fig. 5. In the frequency range up to 50 MHz, curves for $\beta \geq 0.5$ superimpose after division by β, whereas the scaling has broken down at $\beta = 0.2$. At $f = 50$ MHz, we have $kL = 2.1, 0.84, 0.56,$ and 0.42 for $\beta = 0.2, 0.5, 0.75,$ and 1, respectively. A quantitative understanding of these observations seems to be non-trivial. Upon establishing a complete database for the SIS-100/300 kicker impedances, it is therefore necessary to carry out separate simulations

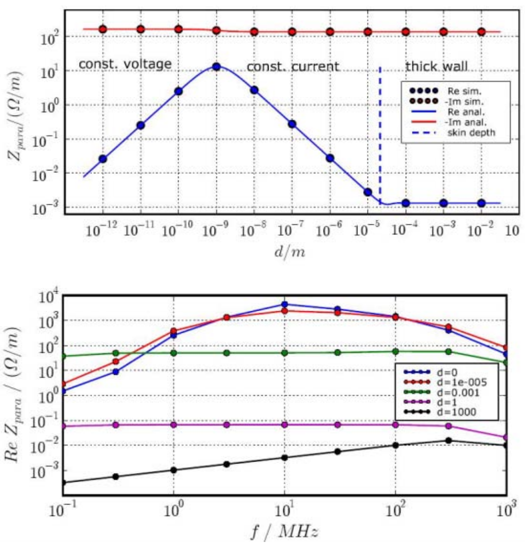

Figure 6: Top: Comparison of $Z_{||}(\omega)$ from analytical calculations and simulations, for the pipe model (see text) at $f = 10$ MHz, $\beta = 0.5$. Bottom: $Z_{||}(\omega)$ per unit length for a 2d cross section of model Fig. 1, with additional copper coating (thickness d given in μm).

for different β, and to interpolate the impedance at values of β not covered explicitly.

INFLUENCE OF METALLIC COATINGS

Screening the kicker ferrite from the beam-induced electromagnetic field by thin resistive layers is a frequently used technique for reducing coupling impedances [10, 6, 11]. As noted above, this is also an option to consider for the SIS-100/300 kickers, in case impedances turn out to be too high in the present design. We have therefore added the possibility of simulating thin resistive layers to our code.

Obviously, the resolution of a layer thickness in the μm regime with the computational grid is not practical. Instead, one uses approximate surface/transition impedance models which connect electric and magnetic fields on both sides of the layer [12]. We have implemented the approach reported in [13]. In order to check its accuracy, we consider the two-dimensional problem of a perfectly-conducting beam pipe of radius 20 cm, into which another, thin-wall, copper pipe of radius 10 cm and wall thickness d is inserted. Analytical expressions for the longitudinal coupling impedance of this model system can be obtained by a slight modification of the calculations reported in [14]. Figure 6, top, shows an excellent agreement of simulations with analytical expressions. This demonstrates that the surface/transition impedance model approximates the exact solution of Maxwell's equations in the copper layer very well. Note that the 'constant current' regime (Fig. 6, top), in which the complete image current is still carried by the copper layer, extends to $d \approx 1$ nm, i.e. to four orders of magnitude below the skin depth.

Next we consider a 2d cut (xy-plane) through the kicker magnet of Fig. 1, where the ceramic beam pipe is now assumed to be coated by a thin copper layer. Figure 6, bottom displays the real part of the longitudinal impedance for different layer thicknesses. Note that for $d = 1$ μm - which is far below the skin depths for the frequency range considered here - the ferrite parts are largely shielded from the beam, a fact also reported in [10]. With such a setup, the problem of ferrite heating would be eliminated, whereas parasitic effects on the kick field buildup (rise time ≈ 200 ns) are expected. The latter is one of the subjects of our further research using 3d simulations.

CONCLUSION

We have reported on our ongoing effort to tabulate the coupling impedances of the SIS-100/300 kickers using electromagnetic field simulations. In the near future, the complete data of all kicker components will be assembled in a user-friendly database.

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