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IMPEDANCE STUDIES OF A CORRUGATED PIPE FOR KARA

S. Maier*, M. Brosi, A. Mochihashi, M. J. Nasse, M. Schwarz,
A.-S. Müller, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

It is planned to install an impedance manipulation structure in a versatile chamber at the KIT storage ring KARA (KArlsruhe Research Accelerator) to study and eventually control the influence of an additional impedance on the beam dynamics and the emitted coherent synchrotron radiation. For this purpose the impedance of a corrugated pipe is under investigation. In this contribution we present first results of simulations showing the impact of different structure parameters on its impedance and wake potential.

INTRODUCTION

In order to be able to meet the increasing demand of experiments at synchrotron radiation facilities such as KARA in terms of brilliance and peak power, a high photon flux and therefore a very high electron density in the storage ring is required. In this regime complex nonlinear phenomena occur due to the interaction of the passing electron bunches with coherent synchrotron radiation (CSR) they emit. This leads to dynamical instabilities and bunch deformations like the so-called microbunching instability. This instability is one of the main road-blocks for increasing the bunch charge. Additionally, the control of the instability can have the benefit of providing an intense source of THz radiation without affecting the X-ray to IR beamlines at storage rings.
At KIT we work on the development and installation of a versatile impedance manipulation chamber into the KARA storage ring in order to study this instability, manipulate the electric wakefields, and eventually affect the beam dynamic of the following electrons. The additional wakefield and impedance will be generated by two vertical parallel plates with periodic corrugations. Bane *et al.* [1,2] have installed such a structure in a linear accelerator and generated narrow-band THz pulses . However, such a structure has not yet been built into a storage ring.

Table 1: Corrugation and Plate Parameters

Parameter	Variable	Range
Half plate distance	b	5 mm to 10 mm
Periodic length	L	50 µm to 200 µm
Corrugtion depth	h	50 µm to 300 µm
Corrugation width	g	12.5 µm to 150 µm
Plate length		100 mm to 200 mm
Taper length		10 mm to 50 mm
Plate thickness		1 mm to 2 mm

A schematic drawing with the characteristic parameters periodic length L, corrugation depth h, periodic gap g and half plate distance b is given in Fig. 1. The theoretical longitudinal impedance $Z^{\parallel}$ of a pair of corrugated planes has been given theoretically in Ng *et al.* [3] for the assumptions $L \lesssim h \ll b$ as

$$\frac{Z_0^{\parallel}}{L} = \frac{Z_0}{\pi b^2}\left[\pi k_r \delta\left(k^2 - k_r^2\right) + i \cdot \mathrm{P.V.}\left(\frac{k}{k^2 - k_r^2}\right)\right] \quad (1)$$

with the resonance wave number $k_r = \sqrt{\frac{2L}{bgh}}$, the wave number $k = \frac{\omega}{c}$, the vacuum impedance Z_0, the δ-distribution, and the principal value P.V.(x).

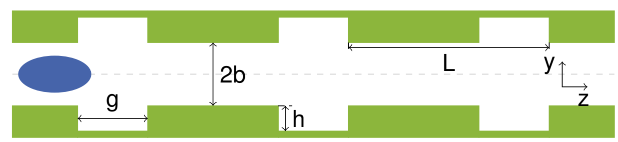

Figure 1: The corrugated pipe in cross section with the relevant geometric parameters is shown. The electron bunch is indicated in blue.

To take also more realistic features of the KARA beam pipe into account we simulated the longitudinal impedance $Z^{\parallel}$ in dependency of the corrugated pipe parameters. For this the software CST Particle Studio [4] was used. The resulting impedance can be characterized by three parameters: resonance frequency f_r, shunt impedance $R_{\parallel}$ and the quality factor Q. For the estimation of these parameters, the impedance has been fitted by a resonator model, described in Ng [5].

The longitudinal wake potential $W^{\parallel}$ for any bunch shape and length can then be estimated from the impedance. P. Schönfeldt has already shown in [6] that the contribution of additional impedance with a strength of about 1 kΩ is negligible above 150 GHz in comparison with the dominant CSR impedance. For this reason, the parameter ranges of the corrugated pipe were chosen so that the theoretical resonance frequency lies between 50 GHz and 150 GHz, where the CSR impedance is suppressed due to the shielding by the beam pipe.

Equation (1) shows that the magnitude of the impedance is heavily dependent on the plate distance. In an experiment at KARA it was determined that the plates lead to a considerable loss of electrons for $b < 5$ mm, as the lifetimes decreases drastically. On this basis the parameters for the simulations were chosen as shown in Table 1. As long as it is not explicitly mentioned, the duty-cycle of the corrugations is 50 % or rather $L/g = 2$. In KARA the space for the chamber is very limited and the length of the corrugated plates is also limited by the necessary vacuum components and taper section. We therefore used a total length of the corrugated structure of 10 cm for all simulations shown here.

* sebastian.maier@kit.edu

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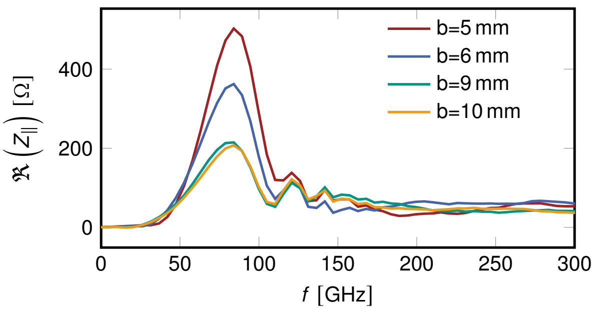

Figure 2: Real part of the longitudinal impedance $Z^\parallel$ for different half plate distances b and fixed corrugation depth $h = 200\,\mu m$ and periodic length $L = 50\,\mu m$. The magnitude of the impedance decreases with increasing plate distance as a consequence of the power law.

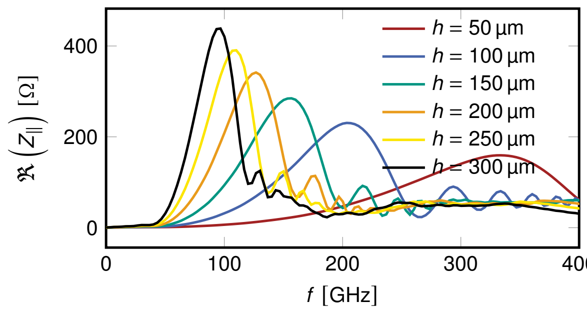

Figure 3: Real part of the longitudinal impedance $Z^\parallel$ for different corrugation depths h and fixed half plate distance $b = 5\,mm$ and period length $L = 100\,\mu m$. A corrugation deepening results in an increase of the shunt impedance, a shift to smaller resonance frequency, and a narrowing of the resonance peak.

SIMULATION

In CST Particle Studio a Wakefield Solver, whose numerical code calculates the wakefields in time domain, is used for the simulation of the corrugated pipe impedance. First, a 3D model of the corrugated structure was created with the modelling tools of CST. The construction comprises only two identical and mirrored corrugated plates made of stainless steel and vacuum in between. To be able to change the total length of the plates or the number of corrugations, a block with 10 corrugations was designed and then joined together as often as needed.

The simulated frequency range of the Wakefield Solver is defined by the −20 dB width of the charge distribution spectrum. For later analysis of the longitudinal beam dynamic with our Vlasov-Fokker-Planck solver Inovesa [7], the impedance is required up to a frequency of 5.2 THz due to the resolution in the temporal structure of the bunch we want to be able to simulate. To reach this frequency a non-physically short Gaussian shaped bunch with a RMS bunch length of $\sigma \approx 0.1$ ps is sent through the structure. In addition, the software is restricted to simulating only line currents/bunches without transverse extension.

For the simulations shown in here, the mesh sizes in horizontal and longitudinal directions are homogeneous. In order to simulate the very small corrugations with sufficient resolution and to reduce the calculation time, the vertical mesh grid in the corrugations (8 vertical cells in the corrugations) is finer than in the vacuum bulk in between.

PLATE DISTANCE

For the design of the complete impedance manipulation chamber the effect of the half plate distance on the impedance is of great interest. In Fig. 2 the real part of the impedance in dependence of the half plate distance b is shown.

It is obvious and corroborated by Eq. (1), that the magnitude of the impedance decreases with increasing plate distance. The behavior $1/b^\gamma$ with $\gamma = 1.27 \pm 0.09$ - as a result of a fit - is not exactly the same as expected from the theoretical model, whose behavior is $1/b^{3/2}$ due to the δ-function and the pre-factors.

Figure 2 also shows, that the resonance frequency and the quality factor (determined by the width of the main peak) are affected very little by the distance of the vertical plates to the beam path. This means that these two parameters of the impedance are purely defined by the parameters of the corrugated plates, which is shown in detail in the following section by using the example of the corrugation depth.

For the construction of the chamber, this means that the strength of the additional impedance can be varied by vertically moving the plates without changing the characteristic of the impedance. This would give an additional tuning knob for the beam dynamic effect in experiment and operation at KARA.

CORRUGATION DEPTH

In order to build the optimal structure with which the microbunching instability can be influenced, it is necessary to understand how the individual parameters of the corrugated pipe influence the impedance of the structure. In Fig. 3 the real part of the longitudinal impedance is shown for different corrugation depths h for a fixed half plate distance $b = 5\,mm$ and period length $L = 100\,\mu m$.

It can be clearly seen that all 3 impedance parameters are influenced by the depth of the corrugations: a corrugation deepening results not only in an increase of the impedance magnitude, but also in a shift to smaller resonance frequencies, as well as in a resonance peak narrowing and thus in a quality factor increase. In future beam dynamics studies it must be examined whether the microbunching structures are much strongly influenced by a broader or narrower impedance.

The resonance frequency, as determined from fits of the impedance to the resonator impedance, in dependence of the corrugation depth is displayed in Fig. 4. We also show a fit with the behavior $1/x^\alpha$ besides the theoretical dependency based on Eq. (1). For these parameter settings the slope is

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$\alpha = 0.671 \pm 0.003$ and thus considerably larger than the value for the theoretical formula ($\alpha_{th.} = 0.5$).

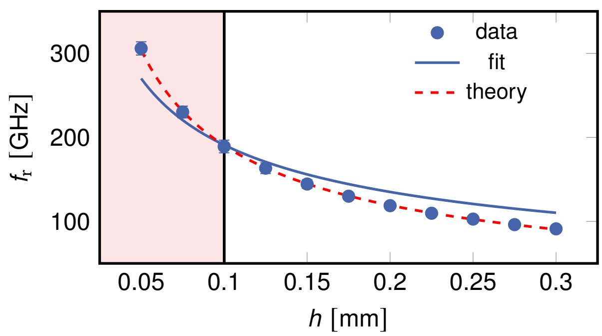

Figure 4: Resonance frequency for different corrugation depths h where the fixed parameters are the same as in Fig. 3. The theory line (red dashed) is based on Eq. (1). The red area shows the parameter range, in which parameter assumptions for the theoretical case are of limited validity.

A systematic deviation of the simulation results from the theory can be seen not only in the different slope but also in an offset for the deep corrugations. The latter effect can be partly explained by the fact that the asymmetry of the resonance peak is not taken into account by the fit leading to a small underestimation of the resonance frequency. However, this does not explain the deviation of the slope. This may be a result of the assumptions for the validity range of the parameters ($L \leq h$ is not fulfilled) and the fact that the higher azimuthal multipole orders are ignored by the formula.

HEAT LOAD ESTIMATION

For the design of the chamber it is necessary to estimate the deposited heat power in the structure because this influences the material choice and the necessary power of the cooling components. In order to determine the power that a bunch loses while passing through the structure, the wake loss factor was calculated for different bunch lengths. Under the assumption of a Gaussian charge distribution with the RMS bunch length σ, the loss factor k_l is defined as [8]:

$$k_l = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{-\infty}^{\infty} W^{\parallel} \cdot \mathrm{e}^{\left(-\frac{s^2}{2\sigma^2}\right)} \mathrm{d}s \tag{2}$$

For this calculation, the wake length was limited to $\pm 5\sigma$, as the charge distribution only makes a relevant contribution in this area. The relation between the wake loss factor and the total deposited power loss is given by [9]

$$P_\mathrm{b} = I^2 \cdot T_0 \cdot N_\mathrm{b} \cdot k_\mathrm{l} \tag{3}$$

with the bunch current I_b, the revolution time T_0, and the number of bunches N_b.

Figure 5 shows the wake loss factor and the corresponding loss power for the setting with the highest shunt impedance (b=5 mm, h=300 µm, L=100 µm, and L/g=1.33). It is obvious that the loss factor decreases with increasing bunch length, although the behavior is not the same as the $1/\sigma$ behavior of a scraper for short bunches [10].

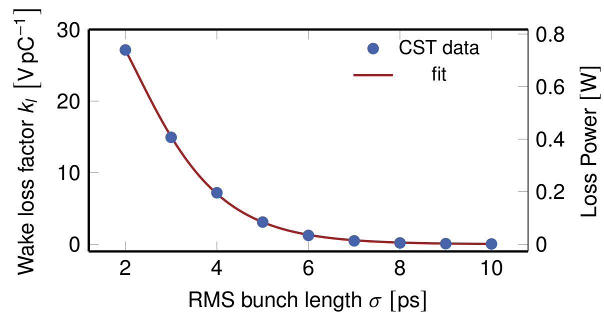

Figure 5: Wake loss factor and loss power in dependence of the RMS bunch length for a single bunch with 100 pC. The corrugated pipe parameters are b=5 mm, h=300 µm, L=100 µm, and L/g=1.33.

For single bunch operation mode at KARA with a bunch charge of 100 pC, which corresponds to 0.271 mA in single bunch current at KARA, a power loss up to 0.75 W is achieved. Thus, especially for the multi bunch operation with higher currents, it is necessary to consider a cooling system for the impedance chamber.

SUMMARY & OUTLOOK

It is planned to install a corrugated pipe structure into the KARA storage ring as an additional, manipulable impedance source to affect the microbunching instability. The results of the impedance simulations show that vertically movable plates would allow a change in magnitude without affecting the shape of the impedance during the operation. The shape of the impedance resonance can be adjusted by the shape and size of the corrugations. Since the parameters cannot be changed easily once the structure is installed, we plan to design a chamber that has multiple corrugated strips.

As a next step, beam dynamics simulations will be carried out to examine the effect of the corrugated pipe impedance and to find the settings with the highest influence on the microbunching instability. Furthermore, we will investigate the design of the necessary taper section providing a smooth transition between the KARA beam pipe and the corrugated structure (and back).

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