NUMERICAL WAKEFIELD CALCULATIONS FOR ELECTRO-OPTICAL MEASUREMENTS *

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Abstract

The technique of electro-optical measurements allows precise and single-shot measurements of the bunch length and shape. The installation of such a near-field setup changes the impedance of the storage ring and the corresponding effects have to be studied carefully. One possibility is to use numerical codes for simulating the wake fields induced by the setup. Such simulations have been done using the wake field solver implemented in the CST Studio Suite [1]. In this paper we present the simulation results together with first measurements.

INTRODUCTION

A setup for electro-optical bunch length and shape measurements has been installed recently at the ANKA storage ring [2]. The measurement principle is based on the effect of a crystal becoming birefringent when it is exposed to an electric field. This birefringence turns the linear polarization of a laser pulse that is sent through the crystal into an elliptical one. At ANKA a 5 mm thick Gallium Phosphide (GaP) crystal and a near-infrared laser (central wavelength 1030 nm) are used. This setup does not only allow to measure the bunch length but also gives the possibility to detect the transversally polarized component of the wake fields that are induced by the bunch traveling through the beam pipe.
Using numerical codes it is possible to calculate these wake fields in the time domain. We are using CST Particle Studio [1], a versatile software that does not allow only to calculate the wake potentials but also the electric field for different points in 3D structures.
In a first step we simulated the longitudinal wake potentials $W_{||}$ and the corresponding wake loss factor k_l (assuming a Gaussian charge distribution with the RMS bunch length σ).

$$k_l = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\infty} W_{||} \cdot e^{\left(-\frac{s^2}{2\sigma^2}\right)} ds \qquad (1)$$

This allows to estimate the power that is lost from the beam when passing the setup.
In a second step we calculated the electric field inside the crystal and compared these results with those from the measurements.

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SIMULATION MODEL

As CST is a 3D code it is possible to import the simulation model directly from CAD-files. In the next step we simplified the model. The setup consists of chamber where the electro-optical crystal mounted on an arm can be moved in and out. This upper part has a coaxial like structure with a length of around 20 cm.
To simplify the model and shorten the calculation time we cut the structure just above the chamber and replaced the coaxial structure with a port with the boundary conditions set to 'open'. This is possible as we only calculate the wake potentials and electric field for time ranges where we do not expect any signal coming back from the coaxial structure after being reflected. A cut through the simulation model is shown in Fig. 1.

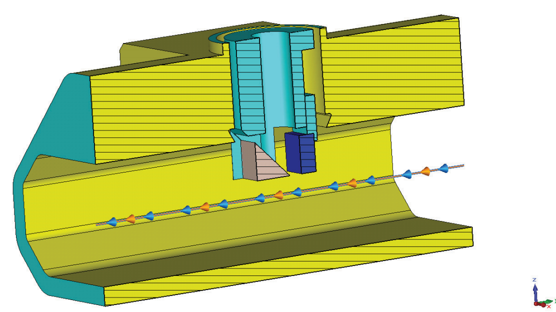

Figure 1: Cross section of the simulation model consisting of the chamber and the holder with the crystal (blue) and the prism (gray) for sending the laser into the crystal and back out again. The electron beam is going from right to left and thus it passes first the crystal and then the prism.

Gallium phosphide shows a dispersive behavior and thus we have a frequency dependency of the dielectric constant ϵ_r [4]. CST is capable to handle this behavior but it showed that for the frequency range we are using (up to 60 GHz) ϵ_r can be set as constant. The other components are made of copper (the chamber) and stainless steel (holder).

For the simulations shown here we are using a homogeneous mesh (i.e. the same size of mesh cells in all dimensions independent of the material properties).

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HEAT LOAD ESTIMATION

During the first measurements in multi-bunch mode we observed a decrease of the intensity of the laser light transmitted through the crystal when we moved the crystal closer to the beam (down to 5 mm) and an increase of the signal when the crystal was moved out (see Fig. 2).

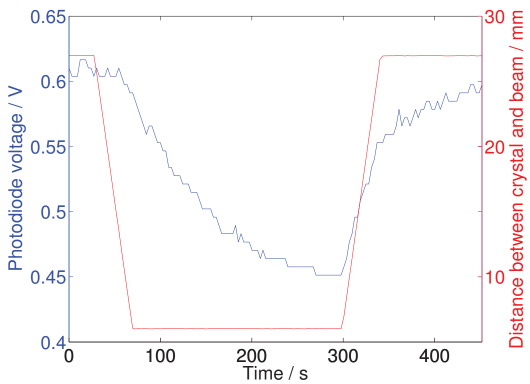

Figure 2: Laser signal (blue curve) and crystal position (red curve), the laser signal drops when the crystal is moved in and increases again when it is moved out. The data were taken in multi bunch operation (31 mA in 33 consecutive bunches)

The exponential decay and the time scale of the signal change leads to the suggestion that the crystal and its holder are exposed to heat power due to wake fields leading to a misalignment of the position sensitive coupling of the laser light back into the fiber. To estimate the power that is lost from the beam when passing the structure, we calculated the wake loss factor for different bunch lengths. The relation between the RMS bunch length and the total power that is lost from the beam is given by the equation 2 ([5]) with the beam current I_b, the revolution time T_0, the number of bunches N_b and the wake loss factor k_l.

$$P_b = \frac{I^2 T_0}{N_b} \cdot k_l \tag{2}$$

By applying this equation for the case shown in Fig. 2 we get the values for the wake loss factor and the power lost from the beam shown in Fig. 3.

It is obvious that the loss factor decreases with increasing bunch lengths, the $\frac{1}{x}$ behavior is the same as expected for a scraper and short bunches [3]. For this simulations we set the wake length to $\pm 5\sigma$ as only in this region the Gaussian charge distribution leads to significant contribution to the loss factor. For bunch lengths that can be achieved for these conditions (31 mA in 33 consecutive bunches), it is possible to achieve values up to 10 W. This amount of lost power led to a damage of the crystal as it was observed when the crystal was replaced during a shut down of the machine.

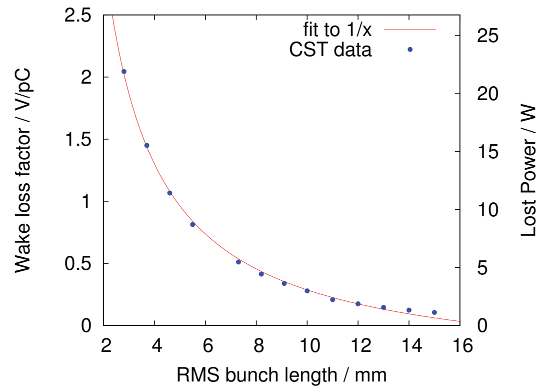

Figure 3: Wake loss factor and loss power calculated for different RMS bunch lengths and 31 mA in one train (33 bunches), the red line is a $\frac{1}{x}$ fit to the data.

CALCULATION OF ELECTRIC FIELDS

The capability of CST Particle Studio to simulate the electric field at all points inside the structure allows for the prediction of the signal that is expected from the electro-optical measurements. These measurements are done using the principle of electro-optical sampling allowing the coverage of a longer time range than with spectral decoding.

The result of such a measurement is shown in Fig. 4 where the ringing due to the wake fields can be clearly seen.

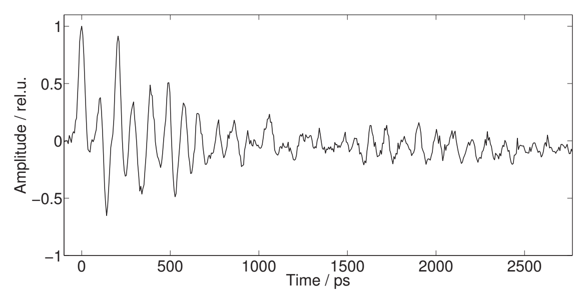

Figure 4: Signal for a single bunch fill measured with electro-optical sampling consisting of Coulomb peak (first peak) followed by some ringing due to wake fields.

The dominating frequency of this ringing is around 10.5 GHz. We simulated the vertical electric field for a point in the crystal (RMS bunch length set to 5 mm). When comparing the two FFT spectra (see Fig. 5), one sees that the they have roughly the same shape but it seems as if there is a systematical frequency shift between measurement and simulation as the dominating frequency of the simulation is around 12 GHz.

To find the reason of this disagreement one has to check the influence of different parameters on the shape of the electric field that is determined by the geometrical properties of the structure as well as the material properties of the crystal. The influence of the crystal's material proper-

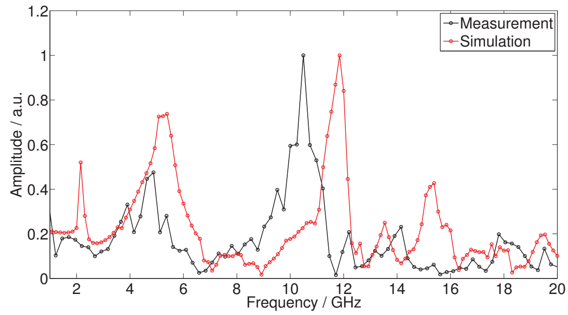

Figure 5: FFT (normalized to 1) of the measured signal from Fig. 4 and the simulated vertical electric field.

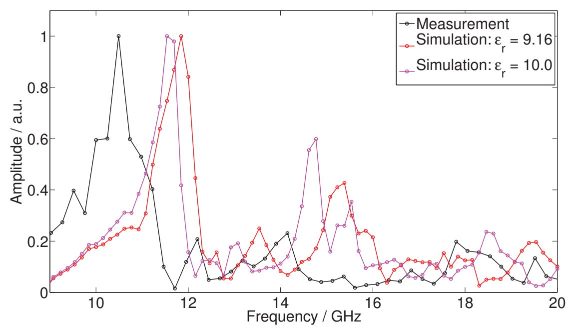

Figure 6: FFT of the measured and the simulated electric field for two different values of ϵ_r normalized to 1. The frequency shift to lower frequencies is obvious but for $\epsilon_r = 10$ some peaks for higher frequencies (above 15 GHz) appear.

ties can be investigated by varying the value of ϵ_r (see Fig. 6)and the thickness. We found that for an increase of the value of ϵ_r the dominant frequency is shifted towards lower values (for $\epsilon_r = 10$ we got 11.5 GHz).

A variation of the thickness of the crystal showed that the frequency is decreasing with increasing thickness but this leads to a stronger deformation of the spectrum and the time signal. Only by changing the properties of the crystal in a reasonable range it is not possible to shift the frequency down to 10.5 GHz and achieve a reasonably good agreement in the time domain as well. By rescaling the time axis of the simulation we can shift the peak in the FFT spectrum to 10.5 GHz. Figure 7 shows the comparison of such a 'rescaled' simulation with the measurements.

It is obvious that the spectra agree well in the time as well as in the frequency domain. In the time domain the amplitude of the measurement is almost the same for measurement and simulation over the whole time range and also the modulation frequencies agree well.

Further studies are required to find the origin of the frequency shift between simulation and measurement by additional parameter scans and modifying the simplifications.

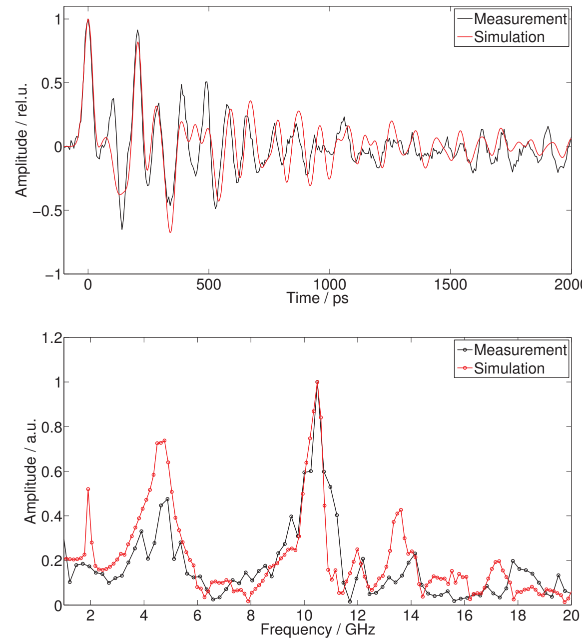

Figure 7: Measured and simulated electric field in the crystal in the time domain (upper plot) and the corresponding FFT spectra normalized to 1. The simulation curves are rescaled in x-direction to achieve a good agreement.

SUMMARY & OUTLOOK

The setup for electro-optical measurements recently installed at the ANKA storage ring gives the unique possibility to directly measure the wake fields induced by the bunches. This allows a comparison with the output of numerical calculations for the wake potentials and electric fields. By using numerical calculations we could also explain the drop of signal intensity when moving the crystal closer to the beam during multi bunch operation by estimating the heat load the crystal is exposed to. Concerning the calculation of the electric field there is a systematical disagreement between the measurement and the simulation model. Once this is overcome it is possible to check the simulated with the measured electric fields and this will allow to use the simulation model for studies of impedance related effects in storage rings.

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